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The Catalan seismic crisis (1427 and 1428): Geological sources and earthquake triggering (H. Perea)

1 **The Catalan seismic crisis (1427 and 1428; NE Iberian Peninsula): Geological**
 2 **sources and earthquake triggering**

3

4

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11

12 **Abstract**

13

14 The Catalan seismic crisis of the years 1427 and 1428 is one of the most destructive
 15 seismic episodes that happened in the northeastern Iberian Peninsula in historical times.

16 The main earthquakes of this crisis occurred on March 19th 1427 in the zone around
 17 Amer ($I_{EMS-98}=VIII$), May 15th 1427 in the vicinity of Olot ($I_{EMS-98}=VIII$) and on February

18 2nd 1428 in the area close to Camprodon ($I_{EMS-98}=IX$). There is much evidence that the

19 Amer fault produced the first two events of this crisis, but is still uncertain which fault

20 generated the earthquake on February 2nd 1428. Using newly available macroseismic

21 data, the earthquake area sources of the three main earthquakes of the crisis have been

22 obtained and they corroborate that the Amer fault may be the origin of the first two

23 events. However, the area source corresponding to the last earthquake of the crisis cannot

24 be associated to a single fault and indicates three possible candidates: the Vallfogona and
25 Ribes-Camprodon thrusts and the Amer normal fault. Modeling of the Coulomb failure
26 stress transfer has been performed to help determine the best candidate responsible for the
27 February event. The results of the modeling points to: a) a triggering relationship between
28 the three main events of the crisis and b) the Amer fault, or a similar extensional fault
29 close and parallel to it, as the most probable origin of the earthquake on February 2nd
30 1428.

31

32 Key-words: Catalan seismic crisis; historical earthquakes; seismogenic faults; earthquake
33 triggering; Coulomb failure stress transfer.

34

35 **1- Introduction**

36

37 To establish the faults that have produced big and potentially destructive earthquakes
38 during the Quaternary and to predict where and, approximately, when the next one might
39 occur are the main objectives of seismotectonic and active tectonic studies. One of the
40 basic ways to localize active faults is to study large historical earthquakes reported on
41 seismic catalogs. From the geographical relationship between the distribution of the
42 damaged localities during one of these large earthquakes and the surrounding geological
43 structure, it may be possible to identify the fault responsible for the event.

44

45 The Catalan seismic crisis constitutes the most destructive seismic episode that has taken
46 place in the northeastern Iberian Peninsula (Fontserè and Iglésies, 1971; Cadiot, 1979;

47 Banda and Correig, 1984; Lambert, 1993; Olivera et al., 2006). The crisis occurred
48 during the years 1427 and 1428 and the study of its three main shocks (figure 1 and table
49 1), March 19th 1427 ($I_{EMS-98}=VIII$), May 15th 1427 ($I_{EMS-98}=VIII$) and February 2nd 1428
50 ($I_{EMS-98}=IX$), and the search for the fault or faults that produced them has been the
51 objective of various studies (Fontserè and Iglésies, 1971; Banda and Correig, 1984; Briais
52 et al., 1990; Ferrer et al., 1999; Fleta et al., 2001; Olivera et al., 2006; Perea, 2006; Perea
53 et al., 2006). The identification of these faults and the recognition of the triggering
54 relation between the main earthquakes may lead to an improvement of future seismic
55 hazard studies performed in this region.

56

57 The objectives of the present work are: a) to assess the location and size of the area
58 sources corresponding to the three main earthquakes of the Catalan seismic crisis,
59 applying the method proposed by Gasperini et al. (1999) and using the new data
60 published by Olivera et al. (2006); b) to try to identify the active faults that produced
61 these earthquakes; and c) to perform a Coulomb failure stress transfer modeling to
62 elucidate the influence of each of them in the occurrence of each other.

63

64 **2- Seismotectonics of the northeastern Iberian Peninsula**

65

66 The active faults located in intraplate regions, such as the northeastern Iberian Peninsula,
67 show low strain rates. Although the seismicity in these regions is low and characterized
68 by earthquakes of low to moderate magnitude, some big earthquakes have occurred in the
69 past, such as those of the Catalan seismic crisis, and could be repeated in the future with

70 important economic and social consequences. Recent studies about the active tectonics of
71 the northeastern Iberian Peninsula show that the slip rate of active faults ranges between
72 0.1 and 0.01 mm/yr and the mean recurrence interval of the big earthquakes lies between
73 10^3 and 10^5 years (Masana, 1995; Masana et al., 2001a; Masana et al., 2001b; Perea et al.,
74 2003; Perea, 2006; Perea et al., 2006). Therefore, the existence of these active faults in
75 low strain regions and its potentiality to produce big earthquakes bring out the necessity
76 to include their study and analysis into seismic hazard projects.

77

78 The northeastern Iberian Peninsula is characterized by the interference between
79 Paleogene compression structures related to the Pyrenees orogen (Muñoz et al., 1986;
80 Vergés and Martínez, 1988; Pujadas et al., 1989; Muñoz, 1992; Muñoz, 2002) and
81 Neogene extensional basins related to the opening of the western Mediterranean (Saula et
82 al., 1996; Tassone et al., 1996; Doglioni et al., 1999; Jolivet et al., 1999; Lewis et al.,
83 2000; Roca et al., 2001; Gelabert et al., 2002). The main Pyrenean structures are thrusts,
84 and associated folds, which have an approximately E-W strike and which dip about 40° to
85 the north (Muñoz et al., 1986). The Neogene extensional basins located in the study area
86 are bounded by mountain fronts, the Transverse ranges, controlled by normal faults with
87 an approximately NW-SE direction with the main ones dipping about 60° to the NE
88 (Saula et al., 1996).

89

90 The instrumental seismicity in the northeastern Iberian Peninsula can be described as
91 moderate to low, given the magnitude and the number of earthquakes (Olivera et al.,
92 1992; Perea, 2006; Perea et al., 2006). The geographic distribution of the earthquakes

93 reveals that the Pyrenees and the Transverse ranges are characterized by a high density of
94 events when compared with the whole area (figure 2a). Regarding the depth distribution
95 of the earthquakes, the seismicity can be described as shallow since more than 90% of the
96 events are located between the surface and 15-20 km depth (figure 2b). This depth
97 approximately coincides with the location of the detachment of the main thrust and
98 normal faults located in the zone. Thus, the active faults may be related to the Pyrenees
99 and the Transverse ranges structures (Perea, 2006; Perea et al., 2006). Moreover, the
100 seismogenic crust might correspond to the first 15-20 km of the crust, taking into account
101 the depth range where the seismicity is mainly located. According to this, the fault
102 rupture planes that will be used in the Coulomb failure stress transfer modeling must not
103 surpass the 20 km depth, the bottom boundary of the seismogenic crust.

104

105 **3- The Catalan seismic crises**

106

107 The Catalan seismic crisis began at the end of February 1427 and lasted until August
108 1428 (Olivera et al., 2006). The first earthquakes were felt in the Girona bishopric at the
109 end of February 1427. During the night between March 2nd and 3rd two earthquakes, that
110 did not produced damage, were felt in Barcelona and in the entire Girona bishopric.
111 Following this, on March 13th, 14th and 15th another three earthquakes struck the same
112 zone, the largest being the one on the 13th ($I_{EMS-98}=VI-VII$) with its epicenter located
113 close to the town of Amer (figure 1 and table 1). These three earthquakes already had
114 produced damage and alarm in the population close to the epicentral area, who began to
115 sleep in tents placed in fields next to the affected cities and towns.

116

117 The first big earthquake of the crisis occurred on March 19th 1427 (figure 1 and table 1).
118 This event produced significant damage in Amer and nearby towns, and was felt in the
119 majority of the Catalan territory and southern France. Olivera et al. (2006) assign to this
120 event a maximum intensity of VIII (EMS-98), a seismic moment (M_0) of $8.43 \cdot 10^{17}$ Nm,
121 a moment magnitude (M_w) of 5.9 and a focal depth of 6 km, and locate the epicenter
122 slightly to the south of Amer. These authors obtained the M_0 using the relationships
123 between this parameter and the area inside a given intensity contour (Johnston, 1996a;
124 Johnston, 1996b), the M_w by means of Hanks and Kanamori (1979) relationship and the
125 focal depth using the Sponheuer (1960) law.

126

127 After the March 19th earthquake, a series of aftershocks occurred in the vicinity of the
128 epicentral zone from March 21st until 22nd, and on April 13th, 22nd and 23rd (Olivera et al.,
129 2006). Among them, the largest was the one on April 22nd, with an assigned intensity of
130 VI-VII (EMS-98) and an epicenter located in the zone of Lloret Salvatge, slightly to the
131 north of Amer (figure 1 and table 1). This aftershock was the first event of the crisis that
132 produced casualties, caused by toxic gas emissions.

133

134 On May 15th 1427 the second big earthquake of the crisis occurred (Fontserè and Iglésies,
135 1971; Olivera et al., 2006). The zone between Olot and the Vall d'en Bas, which is
136 located about 20 km to the north of the area where the previous earthquakes had taken
137 place, was the most damaged (figure 1 and table 1). Olivera et al. (2006) assigned to this

138 earthquake an intensity of VIII (EMS-98), a M_0 of $6.31 \cdot 10^{17}$ Nm, a M_w of 5.8 and a
139 focal depth of 5 km.

140

141 Between May 15th and June 4th 1427 small earthquakes were felt in the Girona bishopric
142 (Olivera et al., 2006). After these, an event of intensity VI (EMS-98) occurred on June 8th
143 and was followed by numerous tremors on June 12th, all of them close to the city of
144 Girona. Following this, on June 14th an earthquake of intensity VII (EMS-98) produced
145 the collapse of half of the town of Caldes de Malavella (figure 1 and table 1), 15 km to
146 the south of the city of Girona. Olivera et al. (2006) assigned to this event a M_w of 5.3.
147 Between June 15th 1427 and February 2nd 1428 several other earthquakes were felt in the
148 vicinity of Girona, mainly between July and August, all of them with intensities lower
149 than V (EMS-98).

150

151 The last of the big earthquakes of the Catalan seismic crisis occurred on February 2nd
152 1428 (Fontserè and Iglésies, 1971; Cadiot, 1979; Banda and Correig, 1984; Lambert,
153 1993; Olivera et al., 2006). This was the largest of the three main events of the crisis and
154 its epicentral zone was located close to the town of Camprodon ($I_{EMS-98}=IX$; Olivera et
155 al., 2006), approximately 15 km to the north of Olot (figure 1 and table 1). This
156 earthquake produced significant damage in the proximity of the epicentral area, more
157 than 1000 casualties and was felt in up to almost 300 km from the epicenter. Olivera et al.
158 (2006) calculated a M_0 of $5.95 \cdot 10^{18}$ Nm, a M_w of 6.5 and a focal depth of 9 km.

159

160 After the earthquake on February 2nd 1428, there are no further data regarding the
161 occurrence of aftershocks, probably eclipsed by the high magnitude and destruction of
162 this last event (Olivera et al., 2006). It is known only that small earthquakes did occur
163 during July and August 1428.

164

165 **4- Earthquakes area sources and seismogenic faults**

166

167 The historical reports describing the damage produced by a certain earthquake in
168 different localities can be used to determine the fault that produced it. Gasperini et al.
169 (1999) proposed a method (“Gasperini method” henceforth), which is based on
170 algorithms developed in Gasperini and Ferrari (1995 and 1997), to assess the location,
171 size and orientation of an earthquake area source using the distribution of the intensity
172 data points, cities or sites where the earthquake caused damage or was felt. The final
173 result of the method is an oriented rectangle that describes the earthquake area source and
174 is meant to represent the surface projection of the fault responsible for the earthquake or
175 the portion of the Earth where it would be likely to be located. The projection of the
176 obtained earthquake area source on a geological map of the area could allow us to
177 determine the fault that was the origin of the historical earthquake. Gasperini et al. (1999)
178 obtained the source of some Italian historical earthquakes with magnitude equal or higher
179 than 5.5, which means intensities equal or higher than VIII (Ambraseys, 1985; López
180 Casado et al., 2000). Therefore, in this study the Gasperini method has been only applied
181 to assess the source of the three main earthquakes of the Catalan seismic crisis (March

182 19th and May 15th 1427 and February 2nd 1428) using the intensity data points published
183 by Olivera et al. (2006).

184

185 Olivera et al. (2006) furnished 49 localities where there is available information about the
186 March 19th 1427 earthquake (22 with assigned intensity, figure 3a; 15 with supposed
187 probable damages; 11 with a felt report; 1 with local effects). The data points with
188 assigned maximum intensity (5 localities with $I_{EMS-98}=VIII$) are located around Amer.
189 The earthquake area source obtained applying the Gasperini method has a NNW-SSE
190 direction, a rupture area of 50.4 km^2 ($8.0 \times 6.3 \text{ km}$) that corresponds to a M_w of 5.7 ± 0.4
191 earthquake and the epicenter is located to the south of Amer (figure 3a and source A in
192 figure 4). When the location of the earthquake area source is projected onto a geological
193 map it shows partial spatial superposition with the southern Amer fault (figure 4). This is
194 an extensional fault located in the Transverse ranges with a NNW-SSE direction and
195 dipping around 60° to the NE (Saula et al., 1996). Therefore, the southern Amer fault
196 could be considered as the fault that generated the March 19th 1427 earthquake. This
197 inference is supported by the conclusions that other authors have made from
198 geomorphologic, geophysical and seismotectonic studies of the Amer fault (Goula et al.,
199 1992; Ferrer et al., 1999; Fleta et al., 2001; Perea, 2006; Perea et al., 2006).

200

201 According to Olivera et al. (2006), the May 15th 1427 affected 38 localities (22 with
202 assigned intensity, figure 3b; 5 with supposed probable damage; 10 with a felt report; 1
203 with local effects). The maximum intensity data points (6 localities with $I_{EMS-98}=VIII$) are
204 located between Olot and the Vall d'en Bas valley, a basin to the west of Olot related to

205 the Amer fault. The Gasperini method gives an earthquake area source located in the Vall
206 d'en Bas zone, with a NE-SW direction and a rupture area of approximately 38 km^2
207 ($6.6 \times 5.7 \text{ km}$) that corresponds to an earthquake of $M_w 5.5 \pm 0.3$ (figure 3b and source B in
208 figure 4). As a result of projecting the earthquake area source on a geological map it
209 could be concluded that the May 15th event was also produced by the Amer fault (figure
210 4). Although there is a discrepancy between the direction of the area source and the
211 direction of the fault, the source is entirely located inside the hanging wall of the Amer
212 fault, clearly pointing to this fault as the origin of the earthquake. In accordance with the
213 area source location, this event was generated by a segment of the fault located to the
214 north of the one that ruptured during the March 19th earthquake, close to where the fault
215 changes its direction from NW-SE to NNW-SSE. The Amer fault being responsible for
216 this earthquake is also supported by other studies (Goula et al., 1992; Ferrer et al., 1999;
217 Fleta et al., 2001; Perea, 2006; Perea et al., 2006).

218

219 For the third and the strongest earthquake of the seismic crises, the February 2nd 1428,
220 Olivera et al. (2006) furnished 136 localities with information about the event (70 with
221 assigned intensity, figure 3c; 36 with damage reported; 27 with probable damage; and 3
222 with insufficient information). The maximum intensity was assigned to the town of
223 Camprodon ($I_{\text{EMS-98}}=\text{IX}$), but around it there are 24 localities with an $I_{\text{EMS-98}}=\text{VIII-IX}$.
224 The earthquake area source obtained applying the Gasperini method is located to the
225 north of the May 15th event epicentral zone, has a WNW-ESE direction and a rupture area
226 of approximately 164 km^2 ($17.1 \times 9.6 \text{ km}$), corresponding to an earthquake of $M_w 6.2 \pm 0.3$
227 (figure 3c and source C in figure 4). In contrast with the previous two analyzed events of

228 the crisis, the projection of the earthquake area source onto the geological map does not
229 show an univocal spatial relationship with one fault. However, it permits three possible
230 candidates: the Vallfogona and the Ribes-Camprodon thrusts and the northern zone of the
231 Amer fault (figure 4). Although Briais et al. (1990) suggested the Tet fault as another
232 possible source for this earthquake, the results here refute this given that the area source
233 obtained does not reveal any kind of spatial relationship with this fault (figure 4).

234

235 **5- Static stress transfer modeling**

236

237 5.1 Coulomb failure stress transfer

238

239 When an earthquake occurs it changes the state of static stress in the surrounding crust.
240 Studies of Coulomb failure stress transfer have shown that the occurrence of moderate to
241 large earthquakes can trigger subsequent earthquakes and exerts some control on the
242 distribution of the aftershocks and quiescent zones (Reasenberg and Simpson, 1992; King
243 et al., 1994; Harris and Simpson, 1996; Hodgkinson et al., 1996; Nostro et al., 1997;
244 Hardebeck et al., 1998; Harris, 1998; Harris and Simpson, 1998; Nalbant et al., 1998;
245 Toda et al., 1998; Parsons et al., 1999; Harris, 2000; Wyss and Wiemer, 2000; Jacques et
246 al., 2001; Lin and Stein, 2004; Martínez-Díaz et al., 2004; Ganas et al., 2005; Ganas et
247 al., 2006; Martínez-Díaz et al., 2006; Nalbant et al., 2006; Parsons et al., 2006; Freed et
248 al., 2007; Heidbach and Ben-Avraham, 2007). In this study, the objectives of the
249 Coulomb stress transfer modeling have been: a) to establish the possible triggering
250 relationships between the three main earthquakes of the Catalan seismic crisis; and b) to

251 identify the fault that generated the February 2nd 1428 event, poorly constrained by the
252 Gasperini method.

253

254 The Coulomb failure stress change caused by the historical earthquakes has been
255 calculated for dislocations in an elastic half-space (Okada, 1992) and on slip planes
256 (“receiver faults” henceforth) with a given strike, dip and rake, or on receiver faults
257 optimally oriented with respect to the regional stress field (Reasenberg and Simpson,
258 1992; King et al., 1994). The Coulomb failure stress change (ΔCFS) is given by:
259 $\Delta\text{CFS}=\Delta\tau_c-\mu'\Delta\sigma_n$, where $\Delta\tau_c$ is the change in shear stress (positive in the direction of the
260 fault slip), $\Delta\sigma_n$ is the change in normal stress (positive in unclamping of the fault) and μ'
261 is the apparent friction coefficient of the fault. According to Nalbant et al. (1998) and
262 taking into account that the majority of the faults located in the study area are normal
263 faults, a value of 0.4 has been selected for μ' . Nevertheless, the variations of this
264 parameter only modestly modify the Coulomb failure stress distribution around a fault
265 (King et al., 1994; Nostro et al., 1997; Stein et al., 1997; Harris, 1998). A positive
266 increase of the Coulomb failure stress transfer in an area is interpreted as meaning that a
267 fault plane located in this area has been brought close to failure, whereas if it is negative
268 the interpretation is the opposite (i.e., relaxed). For the modeling of the Coulomb failure
269 stress transfer the Coulomb 3.1 software (Lin and Stein, 2004; Toda et al., 2005) has been
270 used.

271

272 5.2 Present regional stress field

273

274 The Coulomb stress transfer modeling on optimally oriented receiver faults is most
275 sensitive to the regional stress field orientation (King et al., 1994). Therefore, it is
276 necessary to know the present regional stress field, which in northeastern Iberia has been
277 evaluated using borehole breakout data (Jurado and Muller, 1997; Schindler et al., 1998)
278 and focal mechanisms (Goula et al., 1999; Herraiz et al., 2000; de Vicente et al., 2008).
279 However, the different studies show neither a single tectonic regime nor a homogeneous
280 orientation of the stress field.

281

282 Jurado and Muller (1997) and Schindler et al. (1998) obtained from borehole breakout
283 data that the maximum horizontal stress in the NE Iberian Peninsula has an orientation
284 between NE-SW and ENE-WSW. The latter authors proposed a tectonic regime varying
285 between extensional and strike-slip for the faults located on the north-western margin of
286 the Valencia trough. Therefore, the maximum (σ_1) and intermediate (σ_2) stresses may be
287 similar in magnitude, but clearly different from the minimum stress (σ_3) that is horizontal.

288

289 Goula et al. (1999) and Herraiz et al. (2000) evaluated the present stress field tensor from
290 first P arrival focal mechanisms through the inversion method of Rivera and Cisternas
291 (1990). The former authors obtained two solutions: a) a strike-slip stress tensor with a
292 shape factor (defined as $R_s = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$) equal to 0.4 and a Q-score=0.854; and b) a
293 compressive stress tensor with $R_s=0.5$ and Q-score=0.852. Both solutions have the
294 compressive axis σ_1 in a sub-meridian position. The latter authors obtained, for the
295 Pyrenees, a strike slip stress tensor solution with $R_s=0.47$, a Q-score=0.86, σ_1 being the
296 maximum horizontal stress axis with an approximately N-S direction. Otherwise, these

297 authors, using the inversion method of Giner (1996), obtained for the eastern Pyrenees an
298 extensional stress tensor with σ_1 vertical and σ_3 with a NNE-SSW direction, a $R_s=0.24$
299 and a $Q\text{-score}=0.98$. Nevertheless, they also mention that the low number of events
300 analyzed (only four) diminishes the reliability of the results. Finally, de Vicente et al.
301 (2008) calculated the present stress tensor on the Iberian Peninsula from the inversion of
302 populations of moment tensor focal mechanisms. These authors obtained for the eastern
303 Pyrenees an extensional regime, with $R_s=0.65$ and $\sigma_1=68/242$ (dip and strike), $\sigma_2=09/131$
304 and $\sigma_3=21/037$.

305

306 The solution proposed by de Vicente et al. (2008) is only in agreement with the solution
307 proposed by Herraiz et al. (2000) using the inversion method of Giner (1996) and
308 different from those proposed by the other authors (Jurado and Muller, 1997; Schindler et
309 al., 1998; Goula et al., 1999; Herraiz et al., 2000). Whereas the latter authors propose a
310 maximum horizontal stress with a N-S to NE-SW direction and σ_1 or σ_2 being vertical,
311 the former ones propose σ_1 vertical, σ_2 with approximately NW-SE direction and σ_3 with
312 NE-SW direction.

313

314 In the Coulomb failure stress transfer modeling the stress tensor proposed by de Vicente
315 et al. (2008) for the Pyrenean zone will be used considering that: a) there is evidence of
316 Quaternary activity on normal faults located in the Pyrenees and surrounding zones, such
317 as the Lourdes fault (Alasset and Meghraoui, 2005), the Maladeta fault (Ortuño et al.,
318 2008) and the Amer fault (Perea et al., 2006; and the present study); and b) de Vicente et
319 al. (2008) conclude that the stress tensor solutions obtained by using the inversion of

320 moment tensor focal mechanisms show better quality compared to those obtained from
321 first P arrival focal mechanisms.

322

323 5.3 Source and receiver faults

324

325 Source faults are defined as the fault planes that experiment displacement during the
326 earthquake. Therefore, Coulomb stress transfer modeling has been performed considering
327 as source faults the rupture planes corresponding to the March 19th and May 15th 1427
328 events, since the Amer fault is considered the responsible for both events, as stated above
329 (figure 4). Two different possible source faults have been used for each earthquake in the
330 modeling (figure 5), one using the information given by Olivera et al. (2006) (table 2a)
331 and the other using the data obtained by applying the Gasperini method (table 2b). The
332 characteristics of the source faults for each event are epicentral location, M_0 , M_w ,
333 rupture area (RA), depth range and average displacement (table 2). When not available,
334 the RA has been calculated using the empirical relationship between M_w and RA for
335 normal faults proposed by Wells and Coppersmith (1994), the M_0 has been obtained
336 from the relationship between M_0 and M_w and the average displacement has been
337 established using the M_0 expression, both from Hanks and Kanamori (1979) (table 2 for
338 more details). The depth range has been established considering that both earthquakes are
339 shallow (6 and 5 km depth respectively; Olivera et al, 2006), the dimensions of the source
340 faults and the thickness of the seismogenic crust.

341

342 According to the distribution of the intensity data points furnished by Olivera et al.
343 (2006), and for the geographical location of the earthquake area sources obtained from
344 the Gasperini method, the source fault corresponding to the March 19th 1427 earthquake
345 is located close to the southern tip of the Amer fault. Following the same reasoning, the
346 event corresponding to the 15th May 1427 is located slightly to the north of the zone
347 where the fault changes direction from NW-SE to NNW-SSE (figure 5). Both source
348 faults are parallel to the strike of the Amer fault in each zone and dip 60° to the NE.

349

350 As mentioned above, the Coulomb failure stress transfer has been calculated on receiver
351 faults and the modification of their characteristics (strike, dip and rake) also changes the
352 pattern distribution of the stress lobes (Lin and Stein, 2004). In the modeling, the stress
353 change has been calculated on receiver faults optimally orientated with respect to the
354 present stress field, but also on particular receiver faults. In the second case, two different
355 directions and kinematics have been considered according to the faults observed in the
356 zone: a) receiver faults following the Pyrenean direction and kinematics, thrusts with an
357 approximate strike N90°E and dipping around 40° towards the north, as the Vallfogona
358 and Ribes-Camprodon thrusts (Muñoz et al., 1986); and b) receiver faults following the
359 Transverse ranges direction and kinematics, normal faults with strike N145°E and dipping
360 around 60° towards the northeast, as the Amer fault (Saula et al., 1996).

361

362 Considering the two different source faults and the three different receiver fault
363 geometries (optimally oriented and Pyrenees and Transverse ranges directions and
364 kinematics), six Coulomb stress transfer models were performed for the Catalan seismic

365 crisis (figures 6 and 7). The stress change was sampled at 6 km depth, taking into account
366 the focal depths given by Olivera et al. (2006) for the March 19th and May 15th
367 earthquakes, on a horizontal section of 125x100 km with 2.5x2.5 km grid spacing.

368

369 5.4 Results

370

371 The results of the Coulomb failure stress transfer modeling (figures 6 and 7) show that
372 the location of the lobes where the stress increases and decreases are similar in relation to
373 the source faults between models considering the same type of receiver faults. However,
374 the size of the lobes are slightly different; the smallest dimensions are obtained when
375 using the source faults deduced from the Gasperini method, clearly visible when results
376 corresponding to the May 15th 1427 earthquake are compared (figures 6 and 7 second
377 column). The models corresponding to the optimally oriented receiver faults (figures 6a
378 and 7a) show that faults with directions approximately N120°E, almost vertical (dipping
379 between 80° to the SW and 90°) and with a rake implying mainly normal displacements
380 (between -80° to -100°, following the Aki and Richards (1980) convention) are the best
381 oriented with respect to the present stress field.

382

383 The Coulomb stress transfer results for the March 19th 1427 earthquake show that, when
384 the receiver faults are normal faults (figures 6a/b and 7a/b first column), the maximum
385 stress lobes are located to the north and south of the source fault. However, when the
386 receiver faults are thrust faults (figures 6c and 7c first column) the lobes are situated in
387 the area occupied by the source fault and two secondary maximums appear to the NE and

388 SW of it. Similar stress lobes distributions are observed for the May 15th 1427 earthquake
389 (figures 6 and 7 second column). Nevertheless, the models corresponding to the optimally
390 oriented faults (figures 6a and 7a second column) depict a third maximum stress lobe
391 close to the northeastern boundary of the source fault.

392

393 The pattern distribution of the stress lobes suggests that the May 15th earthquake was
394 strongly related to the occurrence of the March 19th event, which produces an increase of
395 Coulomb failure stress in normal faults with NW-SE direction to the north, in the vicinity
396 of the May earthquake source fault (figures 6a/b and 7a/b first column). This relationship
397 between both events is more clearly in the models using the source faults deduced from
398 Olivera et al. (2006) (figures 6a and b first column).

399

400 **6- Discussion: the source of the February 2nd 1428 earthquake**

401

402 According to the Coulomb failure stress modeling, the May 15th 1427 earthquake
403 produced an increase of the stress to the north and south of the source fault in normal
404 receiver faults with an approximately NW-SE direction (figure 8c) and around the source
405 fault in thrust receiver faults with E-W direction (figures 6c and 7c second column). But,
406 what was the fault responsible for the February 2nd 1428 earthquake? As mentioned
407 above, there are three possible candidates: the Vallfogona and the Ribes-Campardon
408 thrust faults, both with E-W direction, and the Amer normal fault, with approximately
409 NW-SE direction.

410

411 Taking into account the stress distribution and the probable triggering relation between
412 the main earthquakes of the crisis (figures 6c and 7c second column), the Ribes-
413 Camprodon thrust fault has little likelihood of being the source of the February 2nd 1428
414 event given the distance between it and the lobe of increased stress obtained when
415 considering E-W thrust receiver faults. Otherwise, considering the same evidence, the
416 Vallfogona thrust fault and the Amer normal fault are better candidates.

417

418 The occurrence of the May 15th 1427 earthquake produced an increase of the stress in E-
419 W thrust receiver faults in a zone where the Vallfogona thrust fault intersects the surface
420 (figures 6c and 7c second column), around 20 km to the south of the city of Camprodon,
421 pointing to this zone as a possible epicentral area. However, the results also show an
422 increase of the stress in normal receiver faults with NW-SE direction, such as the Amer
423 fault, to the north of the May event source fault (figure 8c). Furthermore, some results
424 show that, near the city of Camprodon, the increase of stress is significant and, thus,
425 indicating a favorable zone to locate a normal fault responsible of the final earthquake of
426 the crisis. The only normal fault known in the area to date is the Amer fault. Although it
427 seems not to have sufficient length to produce an earthquake of magnitude around 6.5, if
428 only its surface expression is considered, its subsurface continuation to the north or the
429 presence of another normal fault to the east but closeby cannot be discounted (Losantos et
430 al., 2002; Prof. Josep M^a Casas, Universitat de Barcelona, personal communication). It
431 seems more congruent to expect a normal fault as the source of this last event taking into
432 account that the two previous earthquakes of the crisis were generated by a fault with
433 such kinematics and considering the present stress field given by de Vicente et al. (2008).

434 Then, according to this, the Amer fault or some normal fault parallel to it would be the
435 most probable source of the February 2nd 1428 earthquake, whereas the Vallfogona thrust
436 fault would be a less probable source.

437

438 However, there are still important questions that should be answered: a) can the Amer
439 fault rupture entirely in only one event or does the change in direction of the fault act as a
440 boundary (barrier) between segments that rupture independently?; and b) if all the
441 seismic crises related to the Amer fault followed the same behavior in the past, as
442 described here, should we expect this to continue in the future? The answer to these
443 questions will significantly improve the seismic hazard assessments in this area.

444

445 Finally, the Gasperini method has been of utility to localize the fault responsible of two
446 large historical earthquakes in a zone of low strain rate. Moreover, the results obtained
447 from applying this method have been helpful to define the dimensions and the
448 geographical location of the source faults used in Coulomb failure stress transfer
449 modeling. Although this method not always points to a unique fault as responsible of an
450 historical earthquake as seen with the February 2nd 1428 event and as reported in other
451 works (Perea, 2006; Perea et al., 2006), it has shown its potential to help researchers to
452 localize the fault sources of large historical earthquakes in low strain zones or, at least,
453 the probable area where this fault may be located and, also, that the information it gives is
454 useful to other earthquake modeling studies.

455

456 **7- Conclusions**

457

458 This study corroborates that the Amer fault, in its southern and northern zones, would be
459 the source of the first two main earthquakes of the Catalan seismic crisis, the March 19th
460 and May 15th 1427 events. Also, the Coulomb failure stress transfer modeling points to a
461 triggering relation between the three big earthquakes of the crisis.

462

463 It has not been possible to determine unequivocally the fault that generated the 2nd
464 February 1428 earthquake. However, the results here discussed point to the Amer fault,
465 or some other extensional fault parallel and close to it, as the most probable source of the
466 event. The Vallfogona thrust has less probability to be the source of this event, but cannot
467 be discarded. Finally, the Ribes-Camprodon thrust, still with some uncertainty, and the
468 Tet fault have been discarded as possible fault sources.

469

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471

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477 (Wessell and Smith, 1998).

478

479 **References**

480

481 Aki, K., Richards, P., 1980. Quantitative seismology, theory and methods. Freeman and
482 Company, San Francisco, 948 pp.

483 Alasset, P.-J., Meghraoui, M., 2005. Active faulting in the western Pyrenees (France):
484 Paleoseismic evidence for late Holocene ruptures. *Tectonophysics*, 409(1-4): 39-54.

485 Ambraseys, N., 1985. Intensity-attenuation and magnitude-intensity relationships for
486 Northwest European earthquakes. *Earthquake Eng. and Structural Dynamics*, 13: 733-778.

487 Banda, E., Correig, A.M., 1984. The catalan earthquake of February 2, 1428. *Engineering
488 Geology*, 20: 89-97.

489 Briais, A., Armijo, R., Winter, T., Tapponnier, P., Herbecq, A., 1990. Morphological
490 evidence for Quaternary normal faulting and seismic hazard in the Eastern Pyrenees.
491 *Annales Tectonicae*, 4(1): 19-42.

492 Cadiot, B., 1979. Les effets en France du séisme Catalan de 1428. In: J. Vogt (Editor),
493 *Les tremblements de terre en France*. BRGM, Orleans, pp. 166-172.

494 de Vicente, G., Cloetingh, S., Munoz-Martin, A., Olaiz, A., Stich, D., Vegas, R., Galindo-
495 Zaldivar, J., Fernandez-Lozano, J., 2008. Inversion of moment tensor focal mechanisms
496 for active stresses around the microcontinent Iberia: Tectonic implications. *Tectonics*,
497 27(1).

498 Doglioni, C., Gueguen, E., Harabaglia, P., Mongelli, F., Durand, B., Jolivet, L., Horváth,
499 F., Séranne, M., 1999. On the origin of the W-directed subduction zones and applications
500 to the Western Mediterranean, *The Mediterranean basins: Tertiary extension within the
501 Alpine Orogen*. Geological Society, London, Special Publications, 156, pp. 541-561.

- 502 Ferrer, P., Masana, E., Santanach, P., 1999. Expresión geomorfológica de la actividad
503 reciente de la falla de Amer (NE de la Península Ibérica). *Acta Geol.Hispanica*, 31(1996):
504 17-24.
- 505 Fleta, J., Santanach, P., Goula, X., Martínez, P., Grellet, B., Masana, E., 2001.
506 Preliminary geologic, geomorphologic and geophysical studies for the paleoseismological
507 analysis of the Amer fault (NE Spain). *Netherlands Journal of Geosciences / Geologie en*
508 *Mijnbouw*, 80(3-4): 243-253.
- 509 Fontserè, E., Iglésies, J., 1971. Recopilació de dades sísmiques de les terres catalanes
510 entre 1100 i 1906. *Fundació Salvador Vives Casajuana*, Barcelona, 548 pp.
- 511 Freed, A.M., Ali, S.T., Burgmann, R., 2007. Evolution of stress in Southern California
512 for the past 200 years from coseismic, postseismic and interseismic stress changes.
513 *Geophysical Journal International*, 169(3): 1164-1179.
- 514 Ganas, A., Shanov, S., Drakatos, G., Dobrev, N., Sboras, S., Tsimi, C., Frangov, G.,
515 Pavlides, S., 2005. Active fault segmentation in southwest Bulgaria and Coulomb stress
516 triggering of the 1904 earthquake sequence. *Journal of Geodynamics*, 40(2-3): 316-333.
- 517 Ganas, A., Sokos, E., Agalos, A., Leontakianakos, G., Pavlides, S., 2006. Coulomb stress
518 triggering of earthquakes along the Atalanti Fault, central Greece: Two April 1894 M6+
519 events and stress change patterns. *Tectonophysics*, 420(3-4): 357-369.
- 520 Gasperini, P., Bernardini, F., Valensise, G., Boschi, E., 1999. Defining seismogenic
521 sources from historical earthquake felt reports. *Bulletin of the Seismological Society of*
522 *America*, 89(1): 94-110.

- 523 Gasperini, P., Ferrari, G., 1995. Stima dei parametri sintetici. In: E. Boschi et al.
524 (Editors), *Catalogo dei forti terremoti in Italia dal 461 a.C. al 1980*. ING-SGA, Bologna,
525 pp. 96-111.
- 526 Gasperini, P., Ferrari, G., 1997. Stima dei parametri sintetici: nuove elaborazioni. In:
527 Boschi, E., Guidoboni, E., Ferrari, G., Valensise, G., Gasperini P. (Editors), *Catalogo dei*
528 *forti terremoti in Italia dal 461 a.C. al 1990*. ING-SGA, Bologna, pp. 56-64.
- 529 Gelabert, B., Sàbat, F., Rodríguez-Perea, A., 2002. A new proposal for the late Cenozoic
530 geodynamic evolution of the western Mediterranean. *Terra Nova*, 14: 93-100.
- 531 Giner, J., 1996. Análisis neotectónico y sismotectónico en el sector centro-oriental de la
532 cuenca del Tajo. *Tesi doctoral Thesis*, Univ. Complutense de Madrid, 345 pp.
- 533 Goula, X., Olivera, C., Escuer, J., Fleta, J., Grellet, B., Bousquet, J.C., 1992.
534 Neotectonics and seismicity of the area of the seismic crisis of 1427-28 in Catalonia.
535 *Proceedings of the 22nd General Assembly of the European Seismological Commission*,
536 *Barcelona*: 333-338.
- 537 Goula, X., Olivera, C., Fleta, J., Grellet, B., Lindo, R., Rivera, L.A., Cisternas, A.,
538 Carbon, D., 1999. Present and recent stress regime in the eastern part of the Pyrenees.
539 *Tectonophysics*, 308(4): 487-502.
- 540 Hanks, T., Kanamori, A., 1979. A moment magnitude scale. *Journal of Geophysical*
541 *Research*, 84: 2348-2350.
- 542 Hardebeck, J.L., Nazareth, J.J., Hauksson, E., 1998. The static stress change triggering
543 model: Constraints from two southern California aftershock sequences. *Journal of*
544 *Geophysical Research-Solid Earth*, 103(B10): 24427-24437.

- 545 Harris, R.A., 1998. Introduction to special section: Stress triggers, stress shadows, and
546 implications for seismic hazard. *Journal of Geophysical Research*, 103: 347-358.
- 547 Harris, R.A., 2000. Earthquake stress triggers, stress shadows, and seismic hazard.
548 *Current Science*, 79(9): 1215-1225.
- 549 Harris, R.A., Simpson, R.W., 1996. In the shadow of 1857 - The effect of the great Ft
550 Tejon earthquake on subsequent earthquakes in southern California. *Geophysical*
551 *Research Letters*, 23(3): 229-232.
- 552 Harris, R.A., Simpson, R.W., 1998. Suppression of large earthquakes by stress shadows:
553 A comparison of Coulomb and rate-and-state failure. *Journal of Geophysical Research-*
554 *Solid Earth*, 103(B10): 24439-24451.
- 555 Heidbach, O., Ben-Avraham, Z., 2007. Stress evolution and seismic hazard of the Dead
556 Sea Fault System. *Earth and Planetary Science Letters*, 257(1-2): 299-312.
- 557 Herraiz, M., De Vicente, G., Lindo-Naupari, R., Giner, J., Simon, J.L., Gonzalez-Casado,
558 J.M., Vadillo, O., Rodriguez-Pascua, M.A., Cicuendez, J.I., Casas, A., Cabanas, L.,
559 Rincon, P., Cortes, A.L., Ramirez, M., Lucini, M., 2000. The recent (upper Miocene to
560 Quaternary) and present tectonic stress distributions in the Iberian Peninsula. *Tectonics*,
561 19(4): 762-786.
- 562 Hodgkinson, K.M., Stein, R.S., King, G.C.P., 1996. The 1954 rainbow Mountain-
563 Fairview Peak-Dixie Valley earthquakes: A triggered normal faulting sequence. *Journal*
564 *of Geophysical Research-Solid Earth*, 101(B11): 25459-25471.
- 565 Jacques, E., Monaco, C., Tapponnier, P., Tortorici, L., Winter, T., 2001. Faulting and
566 earthquake triggering during the 1783 Calabria seismic sequence, pp. 499-516.

- 567 Johnston, A.C., 1996a. Seismic moment assessment of earthquakes in stable continental
568 regions .1. Instrumental seismicity. *Geophysical Journal International*, 124(2): 381-414.
- 569 Johnston, A.C., 1996b. Seismic moment assessment of earthquakes in stable continental
570 regions .2. Historical seismicity. *Geophysical Journal International*, 125(3): 639-678.
- 571 Jolivet, L., Frizon de Lamotte, D., Mascle, A., Séranne, M., Durand, B., Jolivet, L.,
572 Horváth, F., Séranne, M., 1999. The Mediterranean basins: Tertiary extension within the
573 Alpine Orogene - An introduction, *The Mediterranean basins: Tertiary extension within*
574 *the Alpine Orogene*, pp. 1-14.
- 575 Jurado, M.J., Muller, B., 1997. Contemporary tectonic stress in northeastern Iberia. New
576 results from borehole breakout analysis. *Tectonophysics*, 282(1-4): 99-115.
- 577 King, G.C.P., Stein, R.S., Lin, J., 1994. Static stress changes and the triggering of
578 earthquakes. *Bull.Seism.Soc.Am.*, 84(3): 935-953.
- 579 Lambert, J., 1993. The Catalanian (1428) and Alpine (1564, 1644) earthquakes: review of
580 research in France. In: M. Stucchi (Editor), *Historical investigation of european*
581 *earthquakes*. CNR, Milano, pp. 145-159.
- 582 Lewis, C.J., Vergés, J., Marzo, M., 2000. High mountains in zone of extended crust:
583 Insights into the Neogene-Quaternary topographic development of the northeastern
584 Iberia. *Tectonics*, 19: 86-102.
- 585 Lin, J., Stein, R.S., 2004. Stress triggering in thrust and subduction earthquakes and stress
586 interaction between the southern San Andreas and nearby thrust and strike-slip faults -
587 art. no. B02303. *Journal of Geophysical Research-Solid Earth*, 109(B2): 2303-2303.
- 588 López Casado, C., Molina, S., Giner, J., Delgado, J., 2000. Magnitude-intensity
589 relationship in the Ibro-Magrebian region. *Natural Hazards*, 22: 271-297.

The Catalan seismic crisis (1427 and 1428): Geological sources and earthquake triggering (H. Perea)

- 590 Losantos, M., Aragonès, E., Berástegui, X., Palau, J., Puigdefàbregas, C., Soler, M.,
591 2002. Mapa geològic de Catalunya 1:250000 (2^a Ed.). Institut Cartogràfic de Catalunya.
592 Generalitat de Catalunya.
- 593 Martínez-Díaz, J.J., Alvarez-Gomez, J.A., Benito, B., Hernandez, D., 2004. Triggering of
594 destructive earthquakes in El Salvador. *Geology*, 32(1): 65-68.
- 595 Martínez-Díaz, J.J., Capote, R., Tsige, M., Villamor, P., Martin-Gonzalez, F., Insua-
596 Arevalo, J.M., 2006. Seismic triggering in a stable continental area: The Lugo 1995-1997
597 seismic sequences (NW Spain). *Journal of Geodynamics*, 41(4): 440-449.
- 598 Masana, E., 1995. L'activitat neotectònica a les Cadenes Costaneres Catalanes. tesi
599 doctoral Thesis, Universitat de Barcelona, 444 pp.
- 600 Masana, E., Villamarín, J.A., Sánchez-Cabañero, J.G., Plaza, J., Santanach, P., 2001a.
601 Seismogenic faulting in an area of low seismic activity: Paleoseismicity of the El Camp
602 fault (Northeast Spain). *Netherlands Journal of Geosciences / Geologie en Mijnbouw*,
603 80(3-4): 229-241.
- 604 Masana, E., Villamarín, J.A., Santanach, P., 2001b. Paleoseismic results form multiple
605 trenching analysis along a silent fault: The El Camp fault (Tarragona, northeastern
606 Iberian Peninsula). *Acta Geológica Hispánica*, 36(3-4): 329-354.
- 607 Muñoz, J.A., 1992. Evolution of the continental collision belt: ECORS-Pyrenees crustal
608 balanced corss-section. In: McClay, K.R. (Editor), *Thrust tectonics*. Chapman and Hall,
609 pp. 235-246.
- 610 Muñoz, J.A., 2002. Alpine tectonic I: the Alpine sustem north of the Betic Cordillera.
611 Tectonic setting; The Pyrenees. In: Gibbons, W., Moreno, T. (Editors), *The geology in*
612 *Spain*. Geological Society (London), pp. 370-385.

- 613 Muñoz, J.A., Martínez, A., Verges, J., 1986. Thrust sequences in the eastern Spanish
614 Pyrenees. *Journal of Structural Geology*, 8(3-4): 399-405.
- 615 Nalbant, S.S., Hubert, A., King, G.C.P., 1998. Stress coupling between earthquakes in
616 northwest Turkey and the north Aegean Sea. *Journal of Geophysical Research-Solid*
617 *Earth*, 103(B10): 24469-24486.
- 618 Nalbant, S.S., Steacy, S., McCloskey, J., 2006. Stress transfer relations among the
619 earthquakes that occurred in Kerman province, southern Iran since 1981. *Geophysical*
620 *Journal International*, 167: 309-318.
- 621 Nostro, C., Cocco, M., Belardinelli, M.E., 1997. Static stress changes in extensional
622 regimes: An application to southern Apennines (Italy). *Bulletin of the Seismological*
623 *Society of America*, 87(1): 234-248.
- 624 Okada, Y., 1992. Internal Deformation Due to Shear and Tensile Faults in a Half-Space.
625 *Bulletin of the Seismological Society of America*, 82(2): 1018-1040.
- 626 Olivera, C., Redondo, E., Lambert, J., Riera Melis, A., Roca, A., 2006. Els terratrèmols
627 dels segles XIV i XV a Catalunya. Monografies n° 30. Institut Cartogràfic de Catalunya,
628 Barcelona, 407 pp.
- 629 Olivera, C., Susagna, T., Roca, A., Goula, X., 1992. Seismicity of the Valencia trough
630 and surrounding areas. *Tectonophysics*, 203: 99-109.
- 631 Ortuño, M., Queralt, P., Martí, A., Ledo, J., Masana, E., Perea, H., Santanach, P., 2008.
632 The North Maladeta Fault (Spanish Central Pyrenees) as the Vielha 1923 earthquake
633 seismic source: Recent activity revealed by geomorphological and geophysical research.
634 *Tectonophysics*, 453(1-4): 246-262.

- 635 Parsons, T., Stein, R.S., Simpson, R.W., Reasenber, P.A., 1999. Stress sensitivity of
636 fault seismicity: A comparison between limited-offset oblique and major strike-slip
637 faults. *Journal of Geophysical Research-Solid Earth*, 104(B9): 20183-20202.
- 638 Parsons, T., Yeats, R.S., Yagi, Y., Hussain, A., 2006. Static stress change from the 8
639 October, 2005 M=7.6 Kashmir earthquake. *Geophysical Research Letters*, 33(6): L06304.
- 640 Perea, H., 2006. Falles actives i perillositat sísmica al marge nord-occidental del solc de
641 València, PhD Thesis Universitat de Barcelona, Barcelona, 382 pp.
- 642 Perea, H., Figueiredo, P.M., Carner, J., Gambini, S., Boydell, K., participants in the
643 Europealeos, 2003. Paleosismological data from a new trench across the El Camp Fault
644 (Catalan Coastal Ranges, NE Iberian Peninsula). *Annals of Geophysics*, 46(5): 763-774.
- 645 Perea, H., Masana, E., Santanach, P., 2006. A pragmatic approach to seismic parameters
646 in a region with low seismicity: The case of eastern Iberia. *Natural Hazards*, 39(3): 451-
647 477.
- 648 Pujadas, J., Casas, J.M., Muñoz, J.A., Sàbat, F., 1989. Thrust tectonics and paleogene
649 syntectonic sedimentation in the Empordà area, sputheastern Pyrenees. *Geodinamica*
650 *Acta*, 3(3): 195-206.
- 651 Reasenber, P.A., Simpson, R.W., 1992. Response of Regional Seismicity to the Static
652 Stress Change Produced by the Loma-Prieta Earthquake. *Science*, 255(5052): 1687-1690.
- 653 Rivera, L., Cisternas, A., 1990. Stress tensor and fault plane solutions for a population of
654 earthquake. *Bull.Seism.Soc.Am.*, 80(3): 600-614.
- 655 Roca, E., Ziegler, P.A., Cavazza, W., Robertson, A.H.F., Crasquin-Soleau, S., 2001. The
656 northwestern mediterranean basin (Valencia trough, Gulf of Lions and Liguro-Provençal

- 657 basins): Structure and geodynamic evolution, Peri-Tethys Memoir 6: Peri-Tethyan rift -
658 Wrench basins and passive margins. Mem.Mus.National Hist.Nat., 186, pp. 671-706.
- 659 Saula, E., Picart, J., Mató, E., Llenas, M., Losantos, M., Berástegui, X., Agustí, J., 1996.
660 Evolución geodinámica de la fosa del Empordà y las Sierras Transversales. Acta
661 Geol.Hispánica, 29(2-4 (1994)): 55-75.
- 662 Schindler, A., Jurado, M.J., Muller, B., 1998. Stress orientation and tectonic regime in the
663 northwestern Valencia Trough from borehole data. Tectonophysics, 300(1-4): 63-77.
- 664 Sponheuer, W., 1960. Methoden zur Herdtiefenbestimmung in der makroseismik /
665 Freiburger Forschungshefte, C88. Akademie Verlag, Berlin, 120 pp.
- 666 Stein, R.S., Barka, A.A., Dieterich, J.H., 1997. Progressive failure on the North Anatolian
667 fault since 1939 by earthquake stress triggering. Geophysical Journal International,
668 128(3): 594-604.
- 669 Tassone, A., Roca, E., Muñoz, J.A., Cabrera, L., Canals, M., 1996. Evolución del sector
670 septentrional del margen continental catalán durante el Cenozoico. Acta Geol.Hispánica,
671 29(2-4): 3-37.
- 672 Toda, S., Stein, R.S., Reasenber, P.A., Dieterich, J.H., Yoshida, A., 1998. Stress
673 transferred by the 1995 M-w = 6.9 Kobe, Japan, shock: Effect on aftershocks and future
674 earthquake probabilities. Journal of Geophysical Research-Solid Earth, 103(B10): 24543-
675 24565.
- 676 Toda, S., Stein, R.S., Richards-Dinger, K., Bozkurt, S.B., 2005. Forecasting the evolution
677 of seismicity in southern California: Animations built on earthquake stress transfer.
678 Journal of Geophysical Research-Solid Earth, 110(B5).

The Catalan seismic crisis (1427 and 1428): Geological sources and earthquake triggering (H. Perea)

- 679 Vergés, J., Martínez, A., 1988. Corte compensado del Pirineo oriental: geometría de las
680 cuencas de antepaís y edades de emplazamiento de los mantos de corrimiento.
681 Act.Geol.Hisp., 23(2): 95-106.
- 682 Wells, D.L., Coppersmith, K.J., 1994. New empirical relationships among magnitude,
683 rupture length, rupture width, rupture area, and surface displacement.
684 Bull.Seism.Soc.Am., 84(4): 974-1002.
- 685 Wessell, P., Smith, W., 1998. New, improved version of the generic mapping tools
686 released. EOS Trans American Geophysical Union, 79(47): 579.
- 687 Wyss, M., Wiemer, S., 2000. Change in the probability for earthquakes in southern
688 California due to the Landers magnitude 7.3 earthquake. Science, 290(5495): 1334-1338.
- 689

690 **Figure captions**

691

692 Figure 1. Schematic geological map of the northeastern Iberian Peninsula with the
693 location of the macroseismic epicenters of the main earthquakes of the Catalan seismic
694 crisis (Olivera et al., 2006). Cities/towns: A: Amer; C: Camprodon; CM: Caldes de
695 Malavella; G: Girona; O: Olot. Mountain ranges and faults (*italics*): AF: Amer normal
696 fault; CCR: Catalan Coastal Ranges; RCT: Ribes-Camprodon thrust; TF: Tet normal
697 fault; TR: Transverse Ranges; VT: Vallfogona thrust.

698

699 Figure 2. Geographical distribution and depth of the instrumental seismicity registered in
700 the northeastern Iberian Peninsula (from Instituto Geográfico Nacional earthquake
701 catalogue between 1900 and 2003). a) Map showing the geographical distribution of the
702 earthquakes; color indicates their focal depth and the circle size their magnitude (m_{bLg}).
703 b) Profile a-a' showing the earthquakes focal depth; the projected earthquakes are located
704 until 50 km to both sides of the profile; the circle size is not related with the earthquake
705 magnitude. Co: Coastline; Py: Pyrenees; TR: Transverse ranges; VT: València trough.

706

707 Figure 3. Maps showing the distribution of the intensity data points and the intensity
708 contours (Olivera et al., 2006) corresponding to the: a) March 19th 1427 earthquake
709 located in the vicinity of the town of Amer; contours corresponding to I_{EMS-98} VIII and
710 VII; b) May 15th 1427 earthquake occurred in the vicinity of the town of Olot; contours
711 corresponding to I_{EMS-98} VIII and VII; and c) February 2nd 1428 earthquake that affected
712 the town of Camprodon and surrounding areas; contours corresponding to I_{EMS-98} VIII,

713 VII, VI and V. Cities/towns: A: Amer; B: Barcelona; C: Camprodon; G: Girona; L:
714 Lleida; N: Narbonne; O: Olot; P: Puigcerdà; Pe: Perpinyà; T: Tarragona; To: Toulouse.
715 Faults (*italics*): AF: Amer normal fault; RCT: Ribes-Camprodon thrust; TF: Tet normal
716 fault; VT: Vallfogona thrust.

717

718 Figure 4. Geological map of the northwestern Iberian Peninsula showing the location of
719 the earthquake source area of the main events of the Catalan seismic crises. Earthquake
720 source areas: A: March 19th 1427; B: May 15th 1427; C: February 2nd 1428. The map is in
721 UTM coordinate system zone 31 northern hemisphere.

722

723 Figure 5. Map showing the geographical location and the dimensions of the source faults
724 used in the Coulomb failure stress transfer modeling. For more information about the
725 source faults see Table 2 and text. Cities/towns: A: Amer; C: Camprodon; G: Girona; O:
726 Olot. Faults (*italics*): AF: Amer normal fault; RCT: Ribes-Camprodon thrust; VT:
727 Vallfogona thrust.

728

729 Figure 6. Maps showing the Coulomb failure stress changes at 6 km depth when using the
730 earthquake source faults deduced from Olivera et al. (2006) data. Maps in the first
731 column correspond to the stress change after the March 19th 1427 and maps in the second
732 to the cumulative stress change after March 19th and May 15th 1427 earthquakes. a)
733 Optimally oriented receiver faults; b) receiver faults following the direction of the
734 Transverse ranges (N145°E and normal faults); and c) receiver faults following the
735 Pyrenean trend (N90°E and thrust faults). See text for more information. Faults: AF:

736 Amer normal fault; RCT: Ribes-Camprodon thrust; TF: Tet normal fault; VT: Vallfogona
737 thrust.

738

739 Figure 7. Maps showing the Coloumb failure stress changes at 6 km depth when using the
740 earthquakes source faults deduced from the Gasperini method. Maps in the first column
741 correspond to the stress change after the March 19th 1427 and maps in the second to the
742 cumulative stress change after March 19th and May 15th 1427 earthquakes. a) Optimally
743 oriented receiver faults; b) receiver faults following the direction of the Transverse ranges
744 (N145°E and normal faults); and c) receiver faults following the Pyrenean trend (N90°E
745 and thrust faults). See text for more information. Faults: AF: Amer normal fault; RCT:
746 Ribes-Camprodon thrust; TF: Tet normal fault; VT: Vallfogona thrust.

747

748 Figure 8. Maps showing the Coulomb failure stress change at 6 km depth in different
749 periods of the Catalan seismic crisis. The earthquakes source faults correspond to those
750 deduced from the Olivera et al. (2006) data and the receiver faults are those following the
751 direction of the Transverse ranges (N145°E and normal faults). a) Map with the location
752 of the March 13th 1427 earthquake macroseismic epicenter, the zone where the seismic
753 crisis began. b) Map with the location of the March 19th 1427 earthquake macroseismic
754 epicenter and the Coulomb failure stress change distribution. c) Map with the location of
755 the May 15th 1427 and February 2nd 1428 earthquakes macroseismic epicenters and the
756 Coulomb stress change distribution corresponding to the occurrence of the March and
757 May events. Cities/towns: A: Amer; C: Camprodon; CM: Caldes de Malavella; G:

758 Girona; O: Olot. Faults (*italics*): AF: Amer normal fault; RCT: Ribes-Camprodon thrust;
759 TF: Tet normal fault; VT: Vallfogona thrust.

760

761

762 **Table captions**

763

764 Table 1. The earthquakes of the Catalan seismic crisis with an assigned magnitude (M_w)
765 | higher than 5.0 (Olivera et al., 2006).

766

767 Table 2. Parameters of the source faults used in the Coloumb failure stress transfer
768 modeling and corresponding to the March 19th and May 15th 1427 events. a) Source faults
769 deduced from Olivera et al. (2006) data; and b) source faults deduced from Gasperini
770 | method.

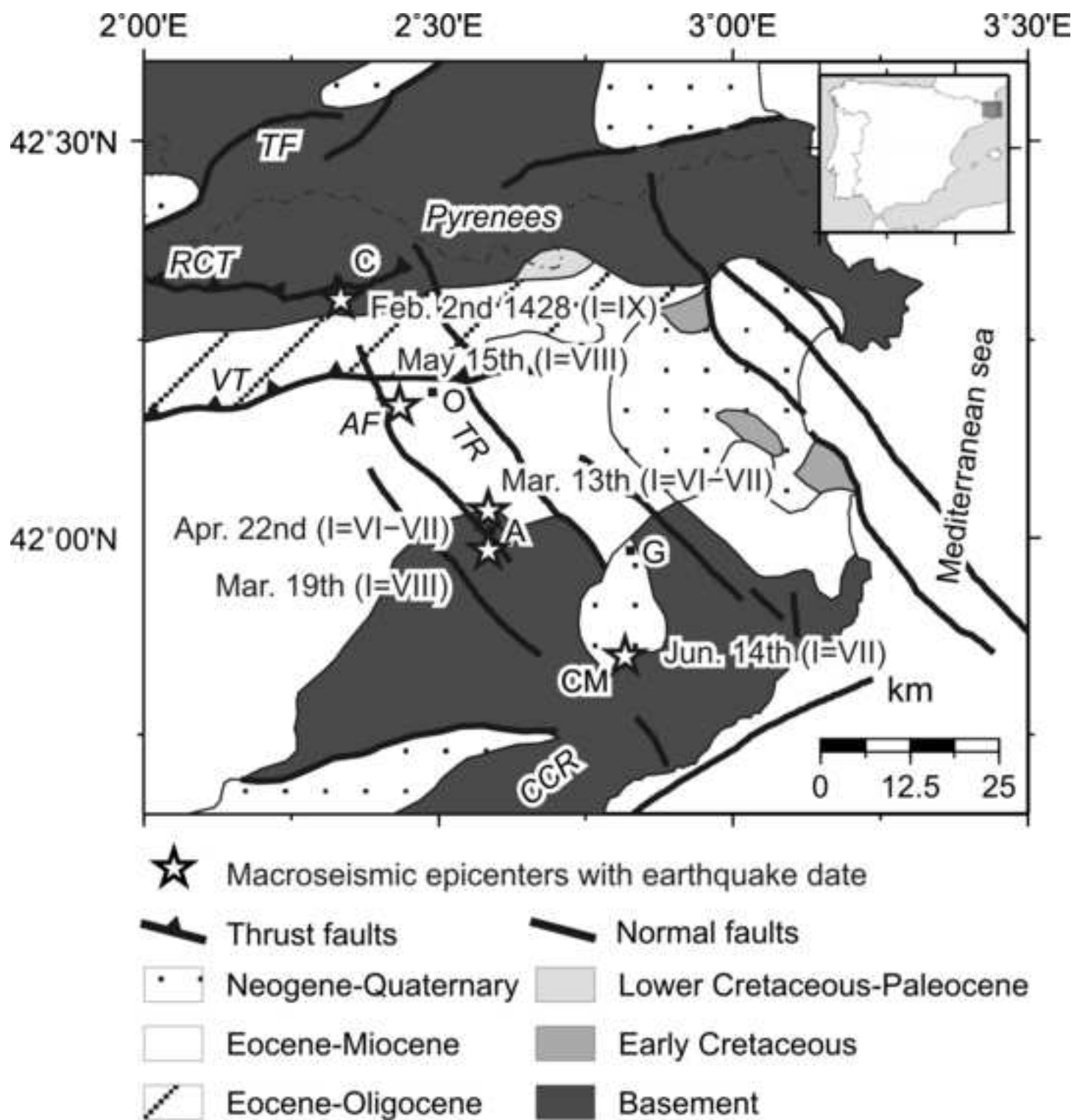


Figure 1 (Press publication)

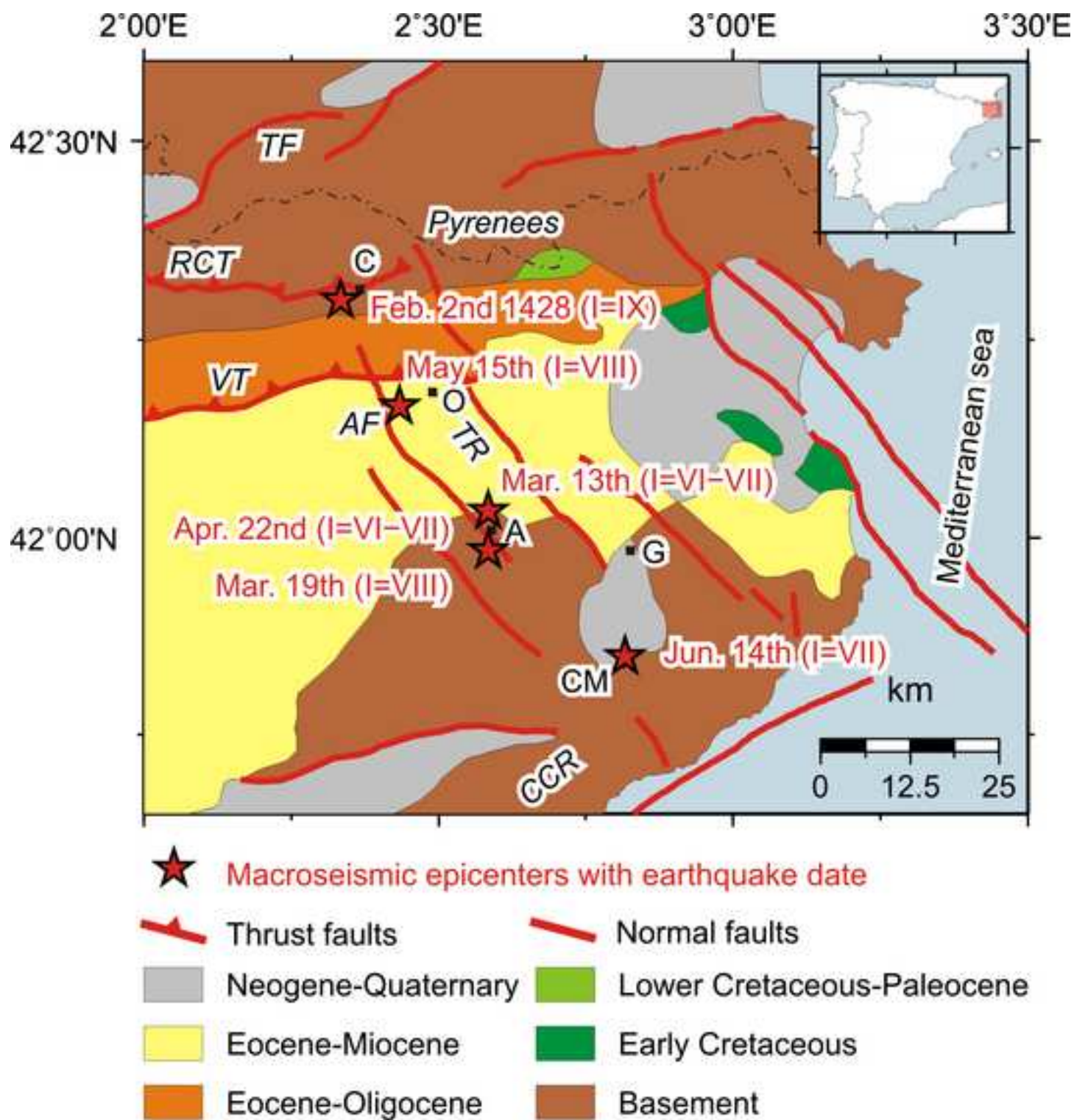


Figure 1 (Online publication)

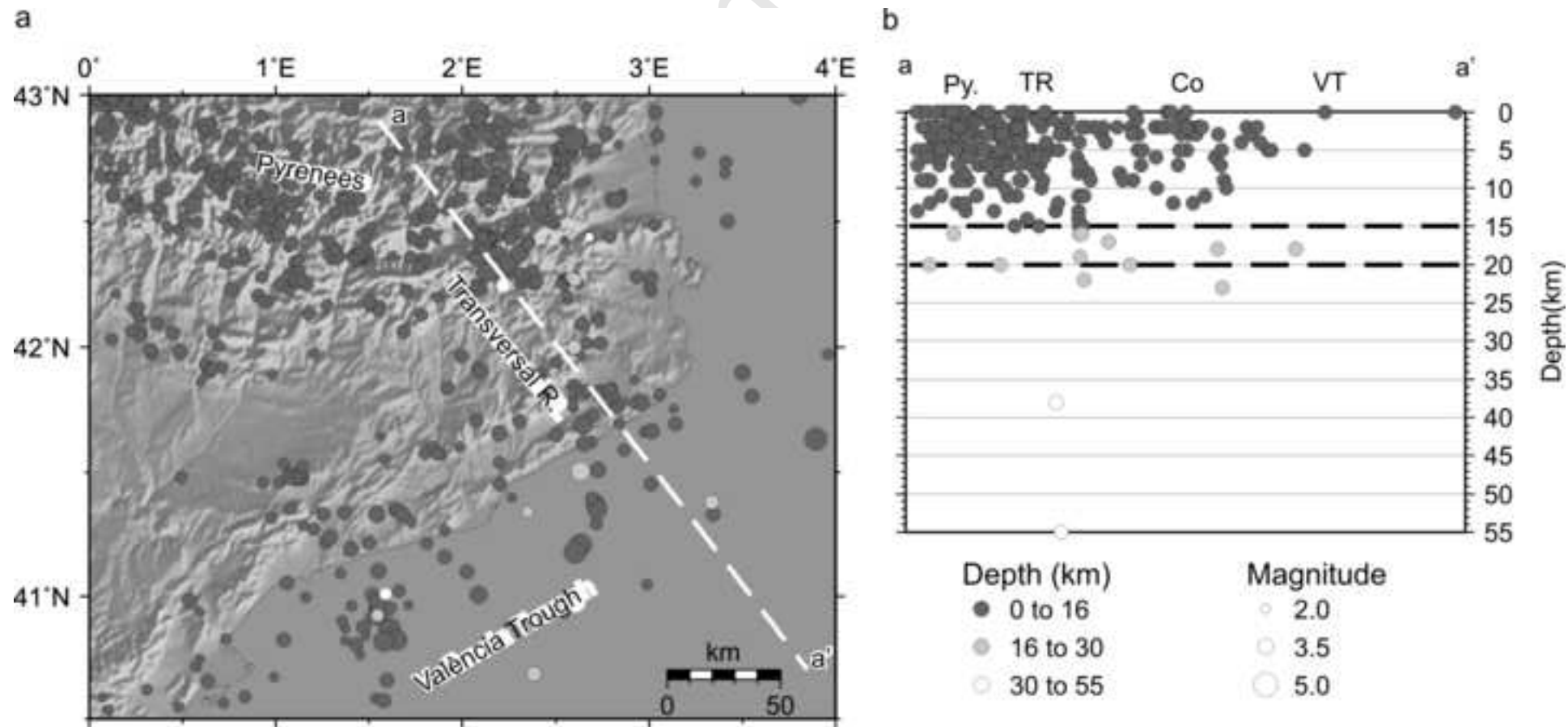


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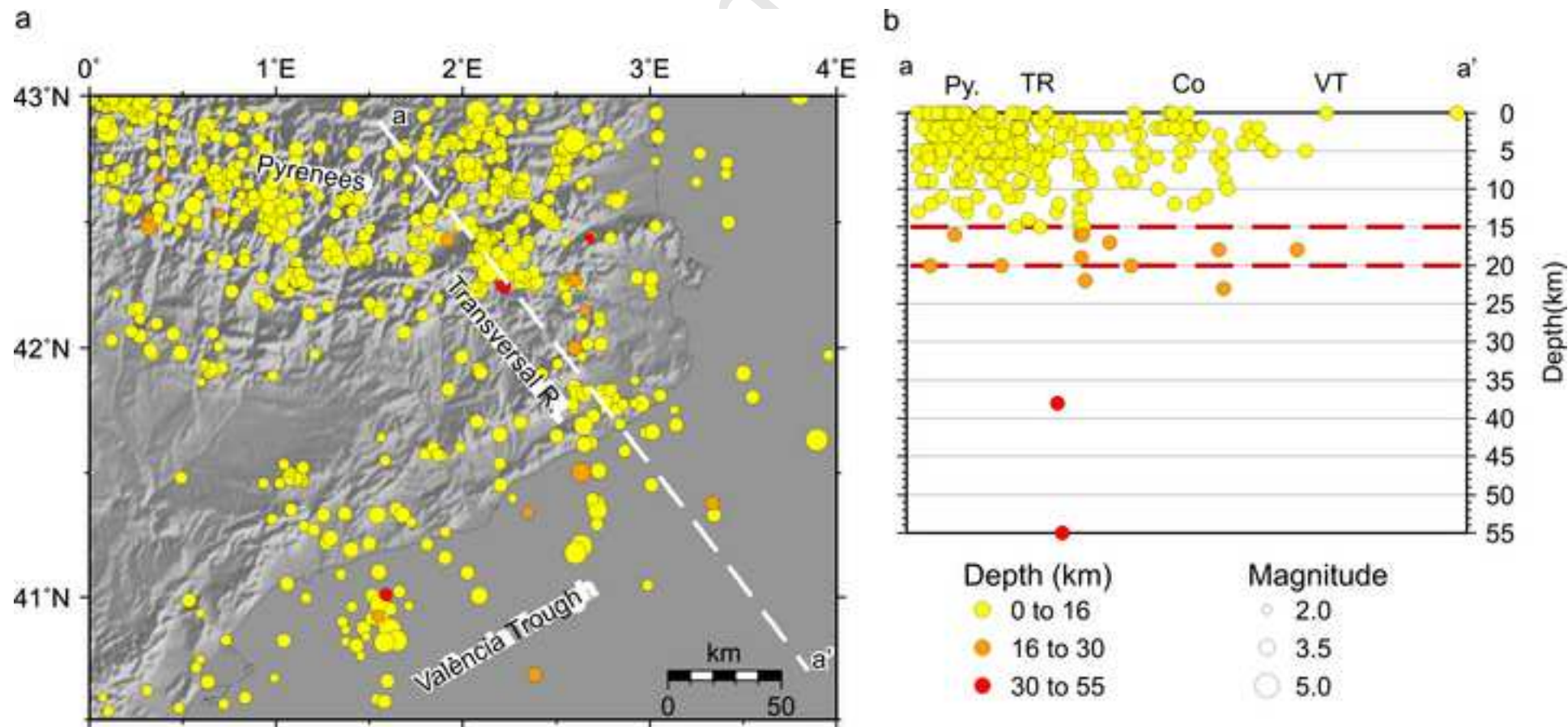


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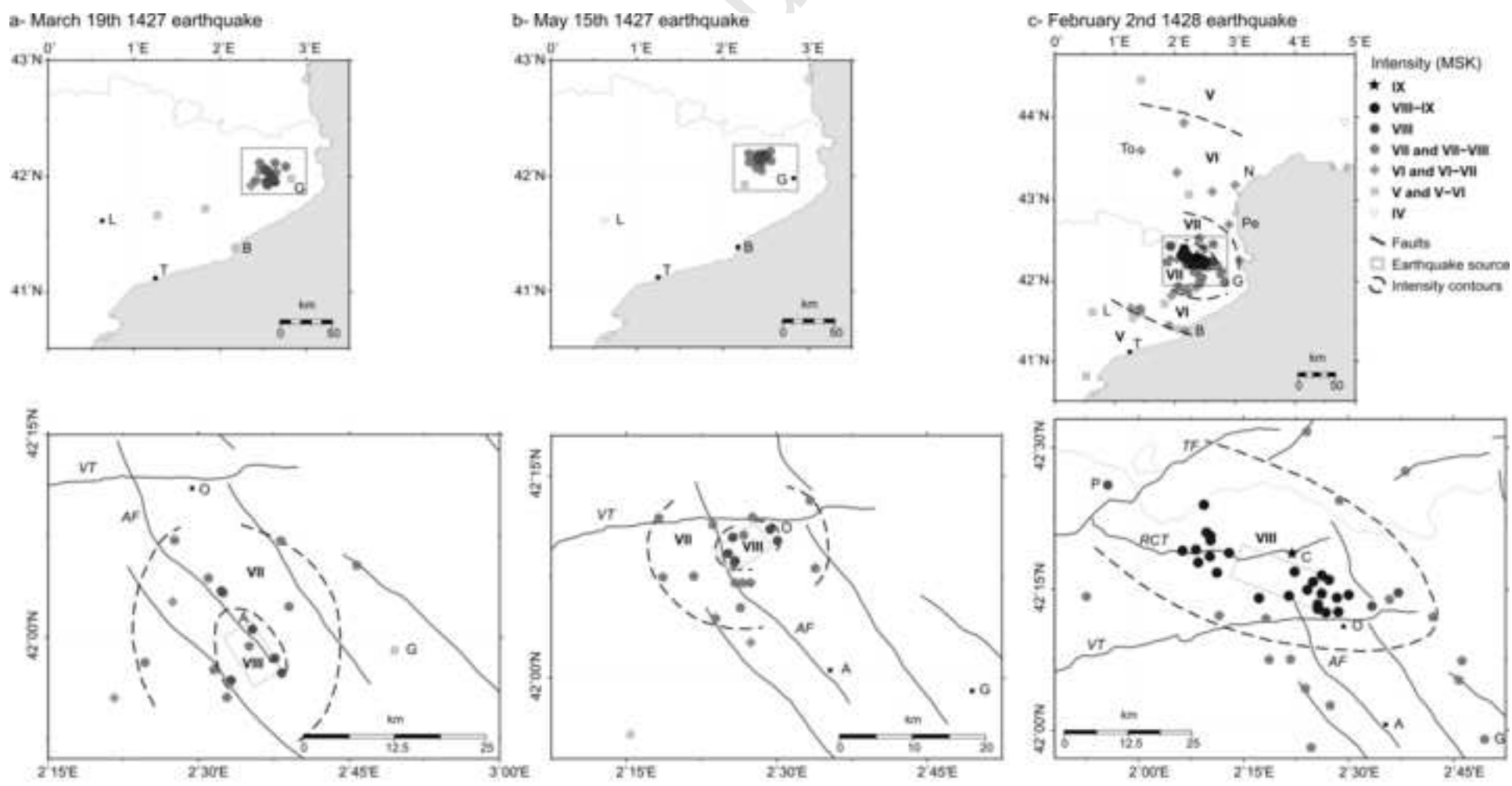


Figure 3 (press publication)

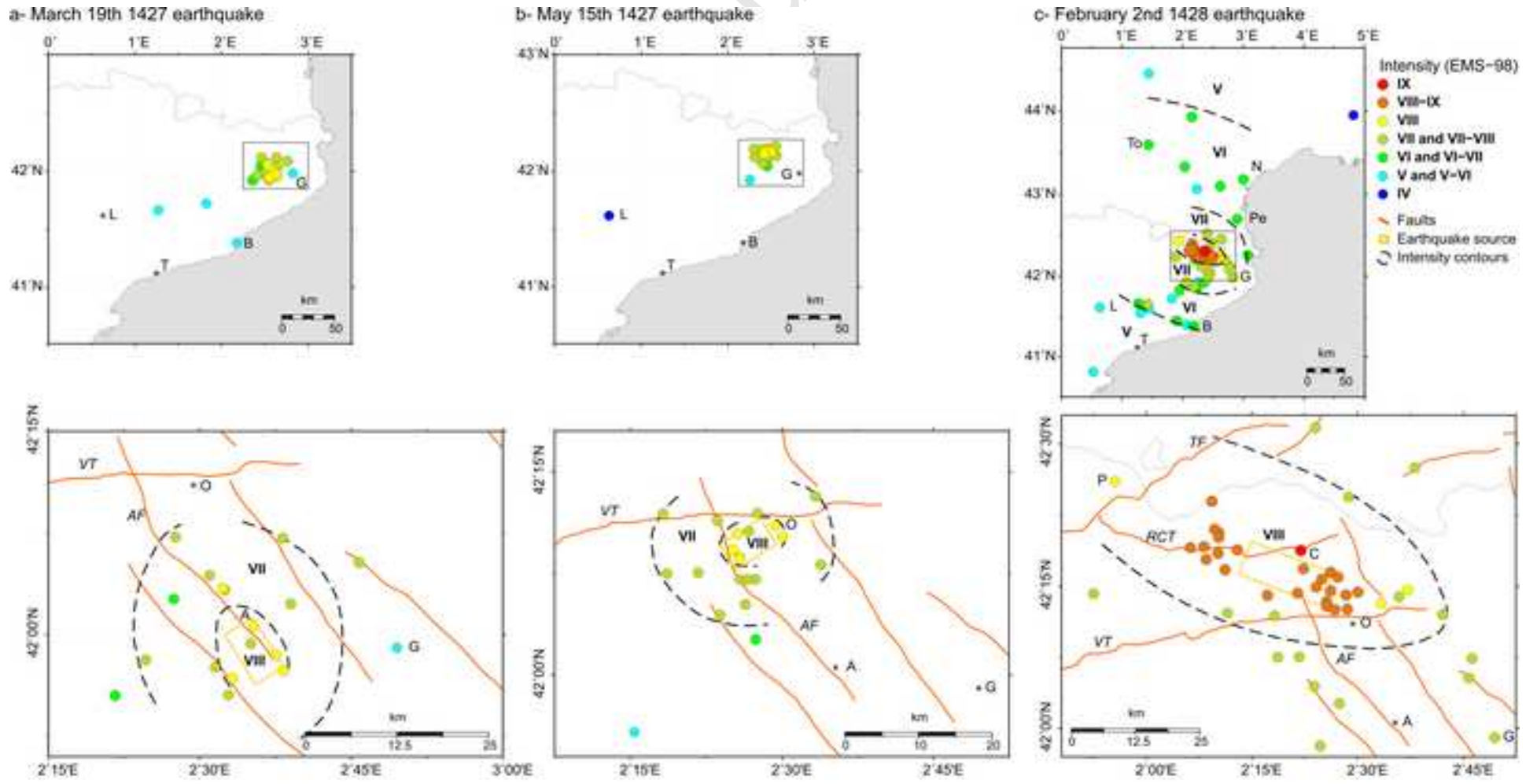


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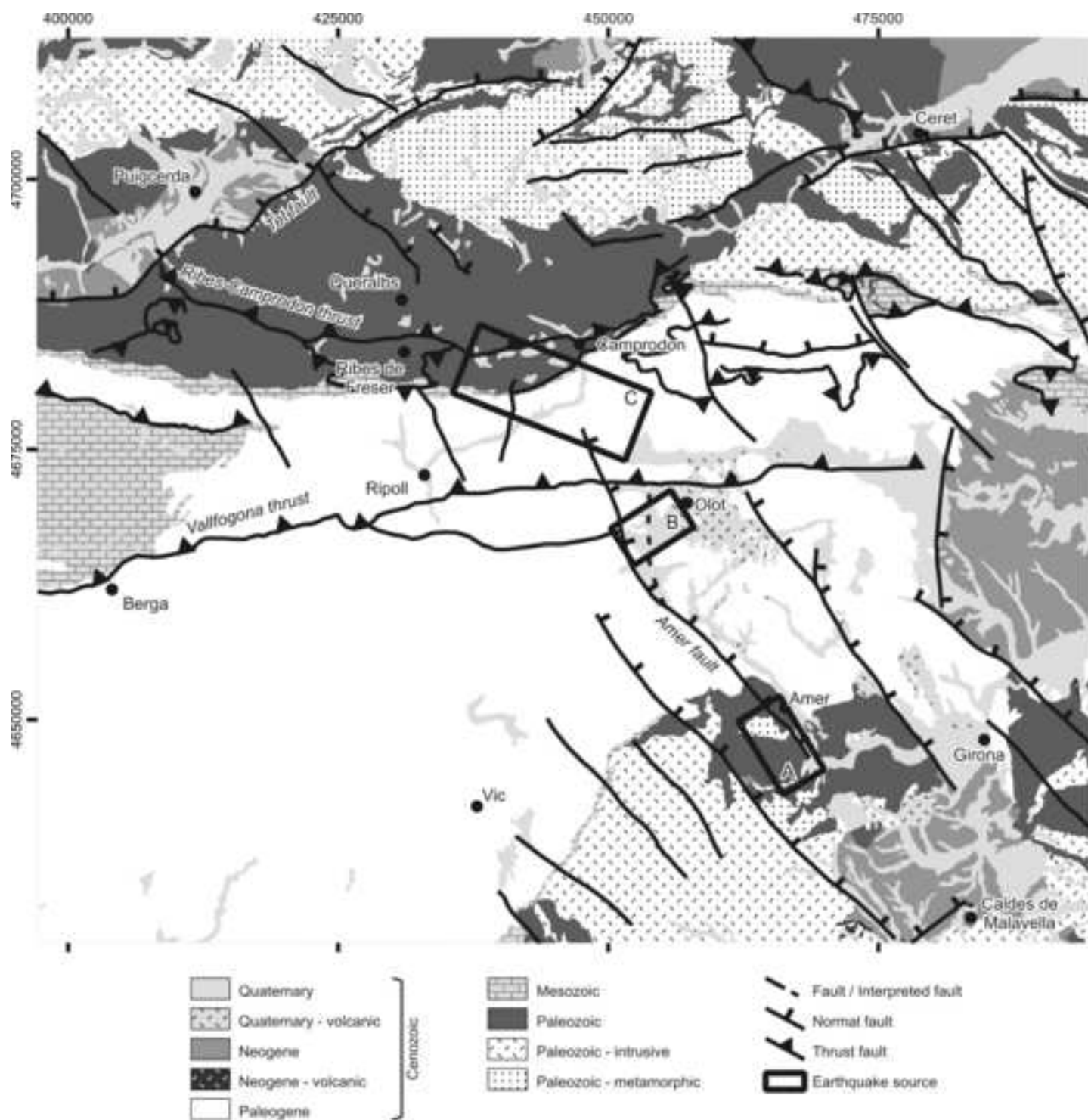


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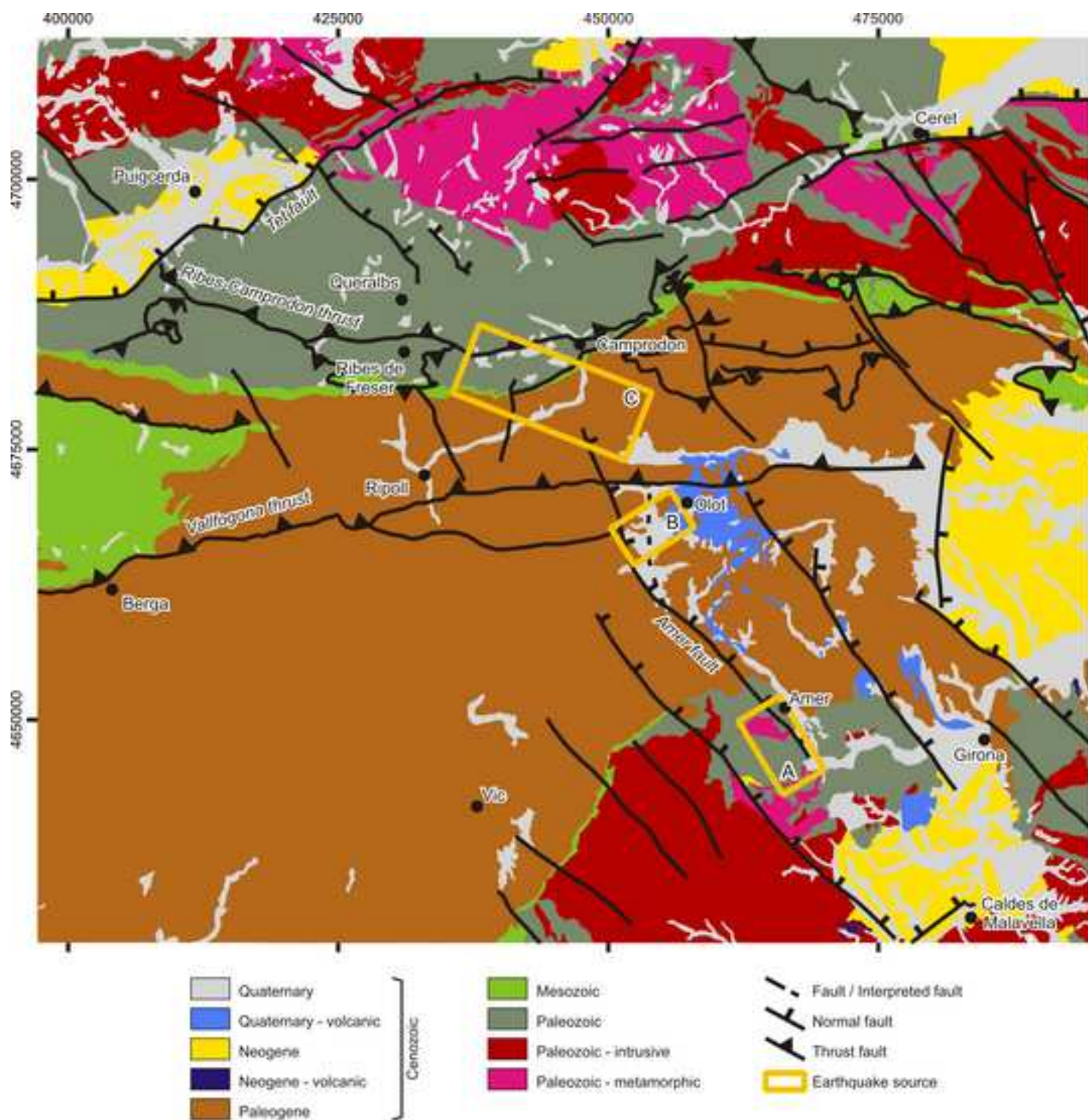


Figure 4 (Online publication)

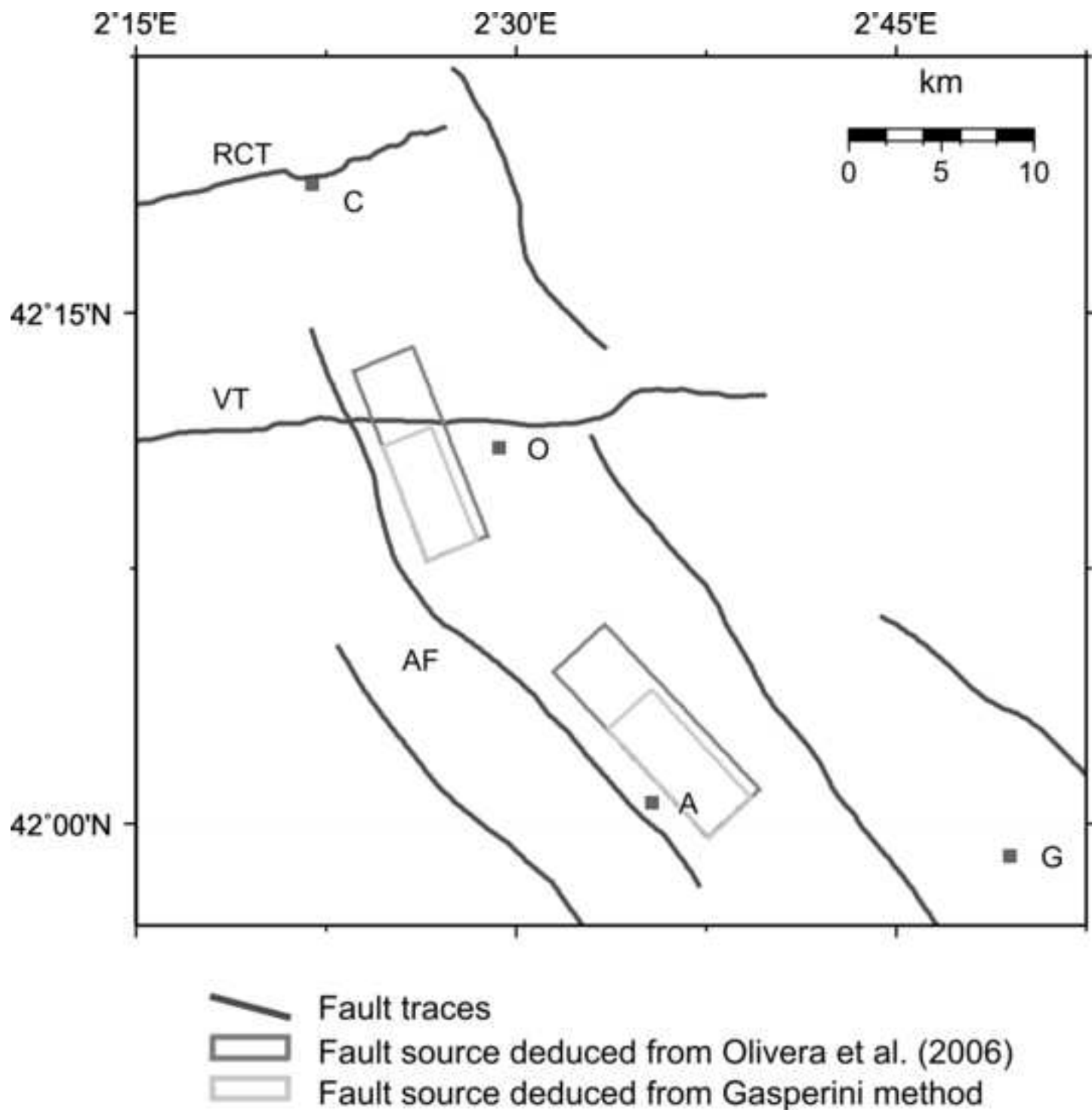


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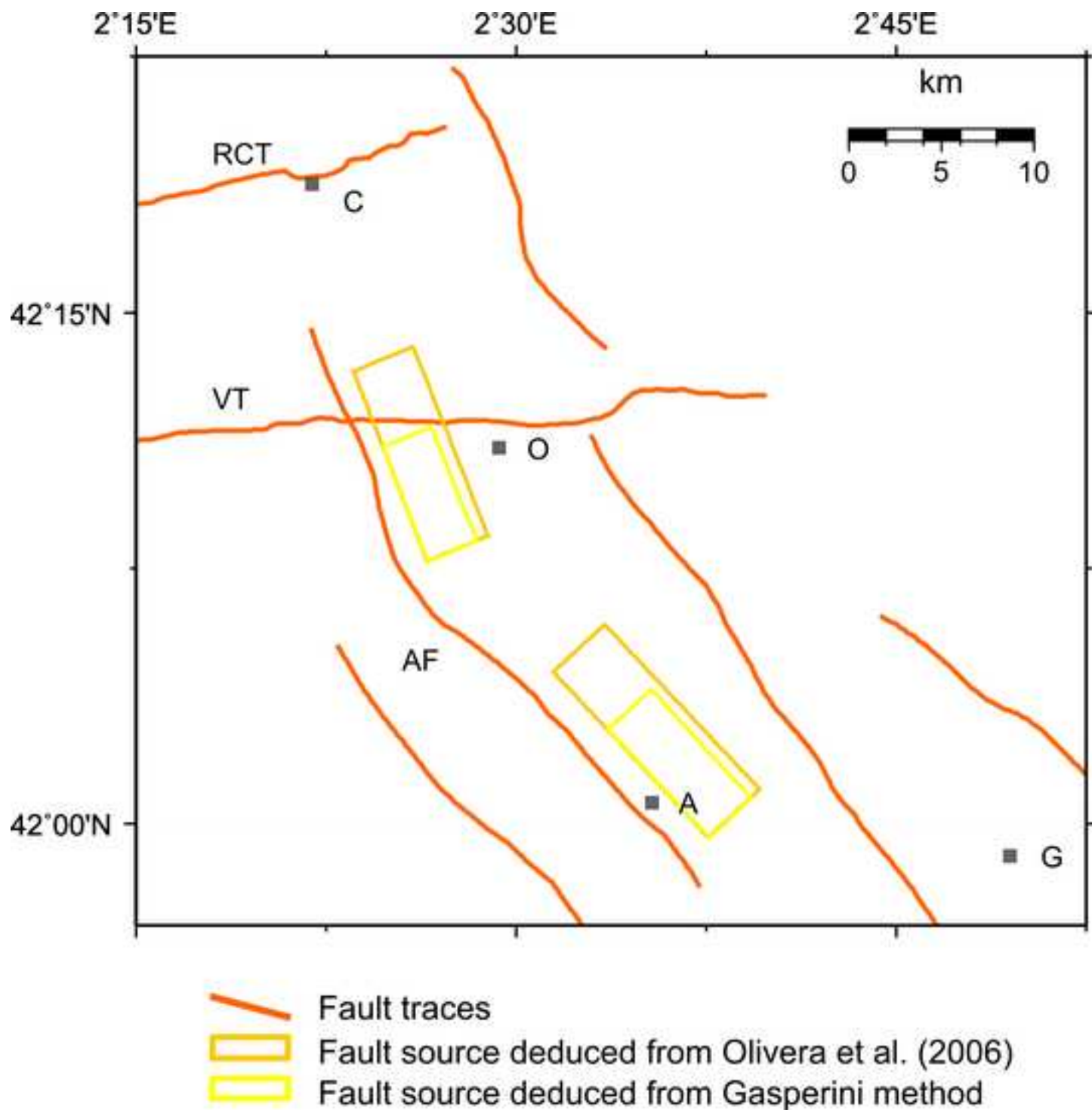


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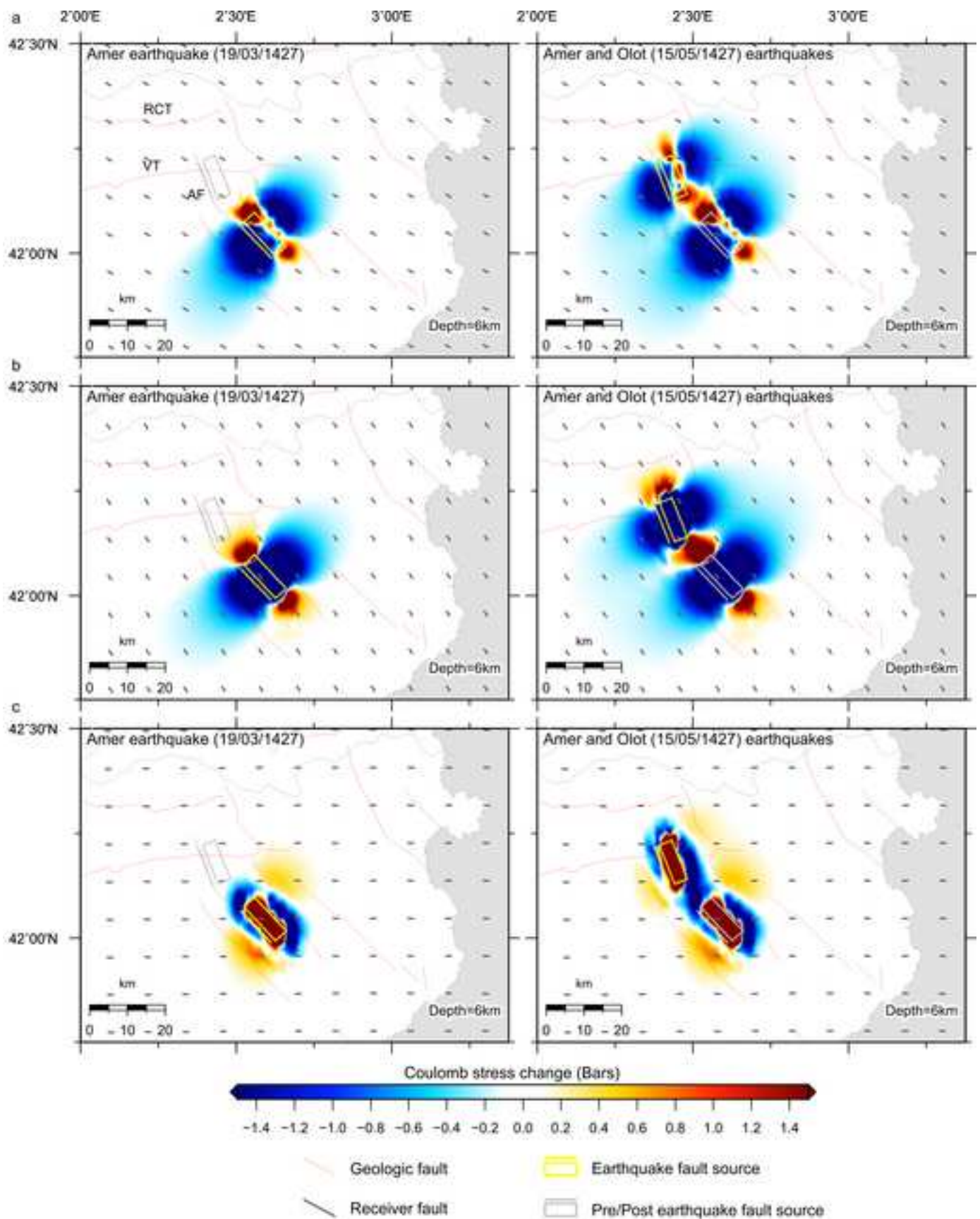


Figure 6

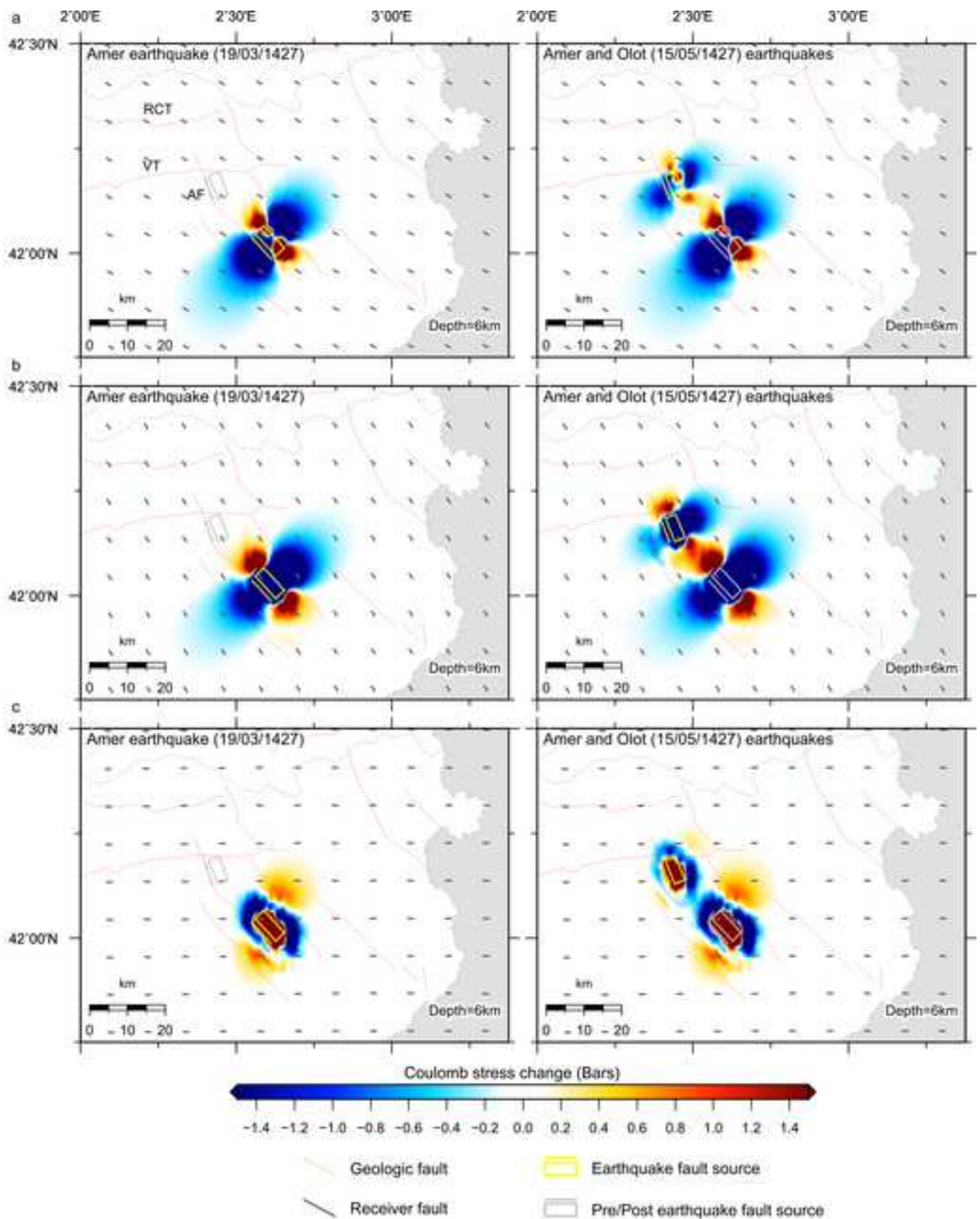


Figure 7

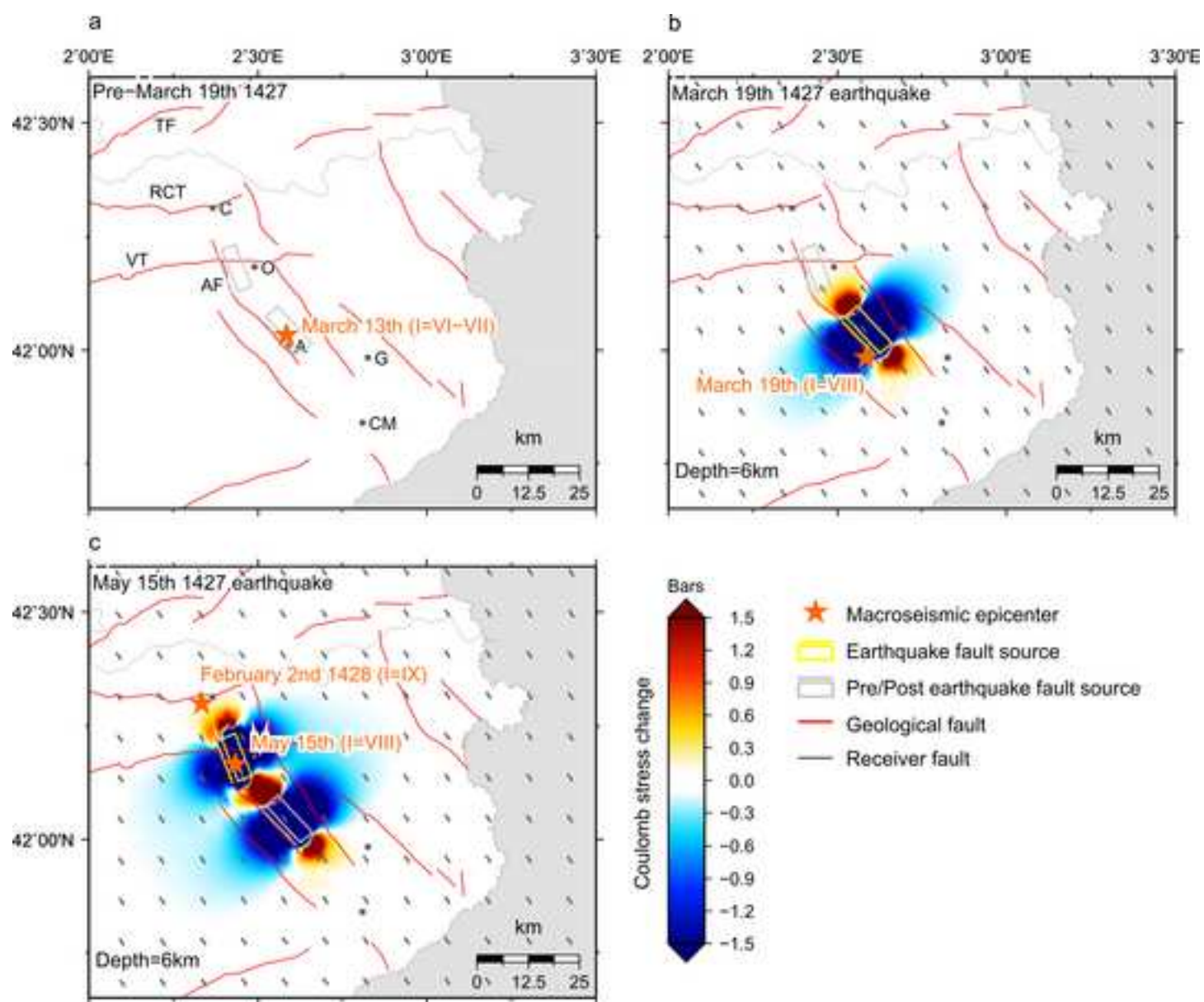


Figure 8

Earthquake	Long epicenter	Lat epicenter	Epicentral intensity (EMS-98)	Mw
March 13 th 1427	2.5833	42.0333	VI-VII	5.0
March 19 th 1427	2.5833	41.9833	VIII	5.9
April 22 nd 1427	2.5833	41.9833	VI-VII	5.0
May 15 th 1427	2.4333	42.1667	VIII	5.8
June 14 th 1427	2.8167	41.8500	VII	5.3
February 2 nd 1428	2.3333	42.3000	IX	6.5

Table 1

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a. Data from Olivera et al. (2006)

Earthquake	Long epicenter	Lat epicenter	Mw	Area (km ²) ¹	Depth range (km)	Mo (Nm)	Average displacement (m) ²
March 19 th 1427	2.5833	41.9833	5.9	92.9	2.5 to 9.0	8.43*10 ¹⁷	0.3
May 15 th 1427	2.4333	42.1667	5.8	76.9	2.5 to 8.5	6.31*10 ¹⁷	0.3

b. Data obtained from the application of the Gasperini method

Earthquake	Long epicenter	Lat epicenter	Mw	Area (km ²)	Depth range (km)	Mo (Nm) ³	Average displacement (m) ²
March 19 th 1427	2.6018	41.9945	5.8	50.4	2.5 to 8.0	6.84*10 ¹⁷	0.5
May 15 th 1427	2.4487	42.1547	5.5	37.6	2.5 to 7.5	2.43*10 ¹⁷	0.2

1 Calculated using empirical relationship between magnitude (M) and rupture area (RA) for normal faults $\log(RA)=-2.87+0.82M$ (Wells and Coppersmith, 1994)

2 Calculated using $Mo=\mu DA$ (Hanks and Kanamori, 1979)

3 Calculated using $Mw=2/3 \log_{10}Mo-6.0$ (Nm) (Hanks and Kanamori, 1979)

Table 2